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The Hydraulic Geometry Of The Lower Portion Of The Sunwapta River Valley Train, Jasper National Park, Alberta

by

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Randolph J. Rice B.Sc.

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE
IN
GEOLOGY

EDMONTON, ALBERTA
fall, 1979

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled The Hydraulic Geometry Of The Lower Portion Of The Sunwapta River Valley Train, Jasper National Park, Alberta submitted by Randolph J. Rice B.Sc. in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE in GEOLOGY.

Nathaniel W Rutter

Supervisor

John Shaw

Gary Parker

J F Lerbekmo

Date Oct. 2, 19 79

Dedication

To my parents for their constant encouragement and financial assistance.

Abstract

Morphologic and hydraulic data were gathered from 60 gravel channels (20/reach) on the Beauty Creek Flats section of the proglacial Sunwapta River during August 4-15, 1977. Four power functions (log-linear ; width, average depth, average surface velocity and water surface slope) are determined for each reach and for Beauty Creek Flats as a whole with discharge as the independent parameter in all cases. A downstream hydraulic geometry interpretation indicates that the downstream reduction in the median grain size, D_{50}, is mainly responsible for the variation in channel behaviour. In all three reaches of Beauty Creek Flats the primary adjustment of the channels to an increased discharge is an increase in the width of the flow.

It appears that the width exponent (b) may be used as an index of braiding intensity.

The b-f-m diagram of Rhodes (1977) is used to determine the at-a-station variation in channel behaviour downstream.

The hydraulic geometry relations determined for Beauty Creek Flats as a whole are compared to corresponding relations from other gravelly, glaciofluvial environments (Fahnestock (1963), Church (1972) and Arnborg (1955)). The best comparison is between the Sunwapta River equations and those of Fahnestock determined for the White River. A difference in channel behaviour between the Sunwapta River and the White River as a group and the Baffin Island sandar (Church) and the Hoffellssandur (Arnborg) as another group

is suggested to be caused by greater bank stability in the Arctic studies.

It is suggested that there is a similarity in channel response among areas of braided gravel outwash provided associated climatic conditions are similar.

The width and velocity relations of Church and the depth relation of this study (eq. 4.14) are suggested for estimating channel response on braided gravel outwash in the Arctic environment. The width and velocity relation of Fahnestock and the depth relation of this study are suggested for similar usage in the non-Arctic environment.

Acknowledgements

Sincere thanks are due to numerous individuals and groups of people constituting departments or belonging to other types of organizations. Without their assistance the successful completion of this study would have been impossible.

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Laboratory of the Highways Division of the government of Alberta is thanked for its loan of coarse sieves and heavy duty beam balance.

Parks Canada, Calgary is sincerely thanked for their issuance of a research and collecting permit without which the field work could not have been conducted. Their staff at the mile 45 warden's station and at the Tangle Creek camp was extremely helpful and co-operative.

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Mr. Bradley Prager was my field assistant. He provided extremely competent and responsible assistance throughout that summer. His friendship and sense of responsibility were greatly appreciated.

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Table of Contents

Chapter

Page

1. Introduction..1

1.1 The Topic...1

1.2 The Objectives Of The Investigation..................6

1.3 The Study Area..6

1.3.1 Location..6

1.3.2 Climate..7

1.3.3 Physiography...9

1.3.4 Surficial And Bedrock Geology..................9

1.3.5 General Description..................................11

2. Developments In The Hydraulic Geometry Approach To Channel Change..25

2.1 Introduction..25

2.2 Two Schools Of Thought..............................25

2.3 General..27

3. Data Acquisition..29

3.1 Equipment Used...29

3.2 Flow Conditions At The Time Of Data Acquisition....31

3.3 Methodology..40

3.4 The Theoretical Discharge Relation.................47

3.5 Laboratory Procedures....................................51

4. The Active Channels Of Beauty Creek Flats...............54

4.1 Morphologic And Hydraulic Characteristics Of The Active Channels..54

4.2 The Hydraulic Geometry Of The Active Channels......68

4.2.1 General..68

4.2.2 Presentation Of The Hydraulic Geometry Relations....74

4.2.3 Interpretation Of Downstream Variation In Channel Behaviour....87

4.2.3.1 Methodology....87

4.2.3.2 Downstream Hydraulic Geometry....88

4.2.3.3 Summary Of The Downstream Hydraulic Geometry....96

4.2.3.4 At-A-Station Downstream Hydraulic Geometry....100

4.2.4 Best Fit Equations For Beauty Creek Flats...105

4.3 Comparison Of The Beauty Creek Flats Channels To Channels From Other Gravelly Glaciofluvial Environments....109

4.3.1 Introduction....109

4.3.2 Comparison To The Channels Of The White River....110

4.3.3 Comparison To Channel Behaviour In Other Gravelly Glaciofluvial Areas....113

4.4 Conclusions....118

REFERENCES....122

Appendix A....127

Appendix B - Flow Cross Sections Of The Theoretical Discharge Data Set....136

Appendix C - Grain Size Data Of The Channel Grab Samples.150

LIST OF FIGURES

Figure		Page
1-1	The Sunwapta River, Jasper National Park, Alberta..........	8
1-2	The daily mean discharge and weather data from the gauging station at the top end of Beauty Creek Flats........	10
1-3	The Sunwapta River at Beauty Creek Flats..................	12
1-4	An upper, middle and lower reach morphology transect from Beauty Creek Flats..............................	14 - 15
1-5	The water surface slope along the dominant active channel on Beauty Creek Flats..................................	16
3-1	The stage - discharge relation for the gauging station at the top end of Beauty Creek Flats.......................	36
3-2	The stage recorder chart for the period August 5-10, 1977 from the gauging station located at the top end of Beauty Creek Flats..	39
4-1	The plotting position of the upper, middle and lower reach of Beauty Creek Flats on Baker and Ritter's (1975) plot of particle size against mean shear stress for coarse bedload material..	63
4-2	Cumulative curves of the grab samples from the upper reach channels of the theoretical discharge data set..............	65
4-3	Cumulative curves of the grab samples from the middle reach channels of the theoretical discharge data set........	66
4-4	Cumulative curves of the grab samples from the lower reach channels of the theoretical discharge data set..............	67
4-5	Log-log plots of the hydraulic geometry relations developed for the upper, middle and lower reach of Beauty Creek Flats and for Beauty Creek Flats as a whole......	79 - 86
4-6	The plotting position of the upper, middle and lower reach of Beauty Creek Flats on the b-f-m diagram of Rhodes (1977).	101

LIST OF TABLES

Table Page

4-1 Statistical summary table of the active channels investigated on Beauty Creek Flats.................... 56 - 58

4-2 The procedure used to estimate the degree of similarity in flow magnitude between the data gathering periods of the upper, middle and lower reach of Beauty Creek Flats.. 73

4-3 The response of channel parameters to an increasing discharge as predicted from Rhodes's b-f-m diagram and as actually occurred on the three reaches of Beauty Creek Flats..................................... 104

4-4 Statistical summary table of the White River channel characteristics of Fahnestock's 1963 study................. 111

4-5 Comparison of the exponents of the hydraulic geometry relations determined for the Sunwapta River at Beauty Creek Flats to the corresponding exponents of the hydraulic geometry relations determined for similar glaciofluvial enviroments................................. 114

LIST OF PLATES

Plate Page

1 A view looking west at the lowermost portion of the upper reach in April, 1977 19

2 A view looking south, up the upper reach during a high flow period 19

3 A view looking west at the uppermost portion of the middle reach in April, 1977 20

4 A view looking west at the uppermost portion of the middle reach in early July, 1977 20

5 A view looking north down the middle reach in July, 1977 21

6 A view looking north down the lower reach in mid-summer 1977 21

7 A view of the gorge cut through silty limestone by the unnamed creek on the western side of Beauty Creek Flats 22

8 A view of discharge from Beauty Creek mixing with the flow on Beauty Creek Flats 22

9 Aeolian loess transport on the middle reach of Beauty Creek Flats on a gusty day 23

10 Avalanche scars on the western valley wall of Beauty Creek Flats 23

11 A southward view from highway 93 of the grassy area located below the lower reach of Beauty Creek Flats 24

12 A view from highway 93 of the center portion of the treed alluvial fan at the bottom of Beauty Creek Flats 24

13 Field assistant with a Price AA current meter at the gauging station at the top of Beauty Creek Flats, June 1977 30

14 A photo of the level used for the field work taken on the upper reach of Beauty Creek Flats in June, 1977 30

15 A downstream view of the gauging station established at the top of Beauty Creek Flats 34

16 A view of the Stevens stage recorder contained within the box attached to the top of the stilling well 35

NOTATION

The following points are to be noted:

1. The use of an overbar in the text indicates a mean value.
2. Some symbols have more than one meaning. The context of its usage will indicate which meaning is appropriate.

SYMBOL(S)	MEANING(S)	DIMENSION(S)
b,f,m,z	exponents of the hydraulic geometry relations for width, depth, velocity and slope, respectively	/
a,c,k,t	coefficients of the hydraulic geometry relations for width, depth, velocity and slope, respectively	/
N	sample size	/
γ	specific weight = ρg ; γ_f - specific weight of fluid; γ_s - specific weight of sediment	$M\ T^{-2}\ L^{-2}$
τ	fluid shear stress; $\bar{\tau}_o$ - average bottom shear stress; τ_b - channel bank shear stress; τ_c - critical shear stress	$M\ L^{-2}$
λ	theoretical discharge correction factor	/
μ	dynamic viscosity of water	$M\ L^{-1}\ T^{-1}$
ν	kinematic viscosity of water = μ/ρ	$L^2\ T^{-1}$
ρ	density; ρ_f - fluid density ; ρ_s - sediment density	$M\ L^{-3}$
u_*	shear velocity = $(\tau/\rho)^{\frac{1}{2}}$	$L\ T^{-1}$

V	velocity of flow; $V_{0.6}$ - velocity at 0.6 of depth of flow ; V_s - surface velocity; V_{st} - theoretical surface velocity; $\bar{V}_{xs}$ - average velocity of flow cross section	$L\ T^{-1}$
S	river stage; channel gradient	L ; /
S_w , S_b	slope of the water surface ; slope of the channel bed	/
D_{50} , D_{90}	50th and 90th percentile of a grain size distribution by weight	L
r^2	the coefficient of determination in a least squares regression	/
Fr	Froude number	/
Re_{ch}	channel Reynolds number	/
n	Mannings n, a total roughness parameter	/
g	gravitational constant	$L\ T^{-2}$
W	channel width at the surface of the flow	L
B^*	dimensionless channel width at the surface	/
d	channel depth	L
d^*	dimensionless channel depth	/
d_c	corrected channel depth	L
a	width to corrected depth ratio	/
R	hydraulic radius of channel ; apparent density of the sediment	L ; /
Q	water discharge	$L^3\ T^{-1}$
$\tilde{Q}$	dimensionless water discharge	/

1. Introduction

1.1 The Topic

This investigation centers on the hydraulic geometry of natural river channels. Hydraulic geometry refers to the manner in which river channel width, depth, and velocity vary in response to a change in discharge of the sediment-water complex. These three parameters can be considered as summary parameters reflecting the net result of complex interactions between the numerous morphologic and hydraulic factors involved in open channel flow in natural river channels. While hydraulic geometry deals specifically with only the relationships between width, depth and velocity to discharge all other morphologic and hydraulic parameters involved in open channel flow are being implicitly considered (Rhodes, 1977, p. 73).

The conventional mathematical model for these relationships is a power function of the form

$$Y = aX^{b}$$

The exponent (b) being the slope of the relationship indicates the sense (positive or negative correlation) and rate of response of the dependent parameter (Y) to changes in the independent parameter (X). The rate of response of the width, depth or velocity (Y) to an imposed discharge (X) is a function of the nature of the channel bed and bank materials which the determine the shape of the channel cross section. The hydraulic geometry exponent is therefore reflecting how a particular channel morphology is responding to the hydraulic characteristics of the flow it is transmitting.

Hydraulic geometry studies may be separated into two categories, namely at-a-station hydraulic geometry and downstream hydraulic geometry. In the former case width-discharge, depth-discharge and velocity-discharge relations are developed for a single (ideally) channel cross section (station) by successive measurements of channel width, depth and flow velocity at different river stages corresponding to different discharges. The emphasis is on variations in the shape of the flow cross section as indicated by the combined changes in cross section width, depth and velocity. In downstream hydraulic geometry studies rather than combine the changes in width, depth and velocity and deal with the flow cross section as a whole, changes in these flow parameters are considered individually in terms of comparing their response to changing discharge at successive downriver locations (channel cross sections).

The discharge variations encountered in at-a-station studies are weather induced and may occur daily, weekly or monthly depending on the frequency of the fluctuations in the weather and on the characteristics of the drainage basin. Weather induced temporal changes in discharge are also reflected in the discharges involved in downstream studies but the primary reason for the change in discharge in these studies is due to the discharge additions from the major and minor tributaries joining a trunk channel at irregular intervals along its length. As a result, in most rivers the total discharge will increase as the distance downstream increases. In many drainage basins the discharge of the major channels are monitored. In these basins the discharge at any point along the trunk channel can be determined by summing the individual discharge contributions of the upstream tributaries. The correlation of changes in width, depth and velocity with changes in discharge at a particular station on a trunk channel and the comparison to similar correlations from other stations along the same channel constitutes downstream hydraulic geometry.

An important concept in downstream hydraulic geometry is that of dominant discharge. A dominant discharge must be stated in any downstream hydraulic geometry study since it should represent the discharge at which or in the area of which the measurements of width, depth and velocity were obtained. As such it represents a type of reference point. At present there is no consensus of opinion as to what flow frequency should represent a dominant discharge (Bray, 1972, p. 14). In reviewing the concept Bray (p. 9-14) presents several definitions of dominant discharge taken from the literature; they are as follows:

1. Inglis (1941) - the discharge which controls the meander length and breadth; it appears to be slightly less than bankfull.
2. Leopold and Maddock (1953) - the mean annual discharge was used as the representative discharge for the determination of the hydraulic geometry relations, however they were not implying that it should be considered as a dominant discharge.
3. Nixon (1959) - the dominant discharge was defined as the bankfull discharge.
4. Leopold, Wolman and Miller (1964) - they stated that the effective discharge can often be approximated by bankfull discharge.
5. Prins (1969) - the dominant discharge was defined by the amount of bedload transport it produced.
6. Blench (1957) - the dominant discharge was defined as that discharge which was associated with the average load of a stream for any long period of time.
7. Benson and Thomas (1966) - dominant discharge was defined as the discharge at which the maximum suspended sediment load is transported.

Bray (p. 14) concludes his review by stating that despite the disparity over the definition of a dominant discharge it is generally accepted that a dominant discharge is a formative discharge, ie. a discharge which is capable of physical alteration of the channel cross section. In the context of the previous discussion where the exponent of the power function was defined as an indicator of the rate of adjustment of the channel cross section to an imposed discharge, the formative nature of a dominant discharge is mandatory.

Equally important to downstream hydraulic geometry studies is the concept of constant frequency of discharge. This concept expresses the necessity of comparing different stations along a river using data that was obtained at discharges of equal flow frequency. For instance, as discussed in Leopold and Maddock's (1953) paper, if data obtained at an upstream station was secured at the mean annual discharge for that station, then to compare its hydraulic geometry to that of a downstream station the data on the latter must have been obtained at its mean annual discharge. The absolute value of the mean annual discharge for the downstream station will exceed that of the upstream station but the frequency of occurrence of the two flows will be the same.

Hydraulic geometry is a tool, a useful means of summarizing the very complicated interactions between the flow and the bed and bank materials of a natural channel (Rhodes, 1977, p. 94). The utility of hydraulic geometry studies lies in the predictive capability of the equations which define the response of the channel and flow parameters. These equations serve as indicators of channel behaviour as a function of discharge and as such become important sources of information to anyone concerned with the response of a particular river channel to changes in its discharge.

1.2 The Objectives Of The Investigation

Morphologic and hydraulic data was acquired from the gravel channels of the study area with the following objectives in mind:

1. The characterization of the morphologic and hydraulic nature of the active channels.
2. The determination of a variation in channel behaviour through the development of hydraulic geometry relations and the interpretation of the cause of this variation.
3. A comparison to channel behaviour in other areas of gravelly braided outwash.
4. The selection of hydraulic geometry relations which could be used as estimators of channel behaviour in any area of gravelly braided outwash.

1.3 The Study Area

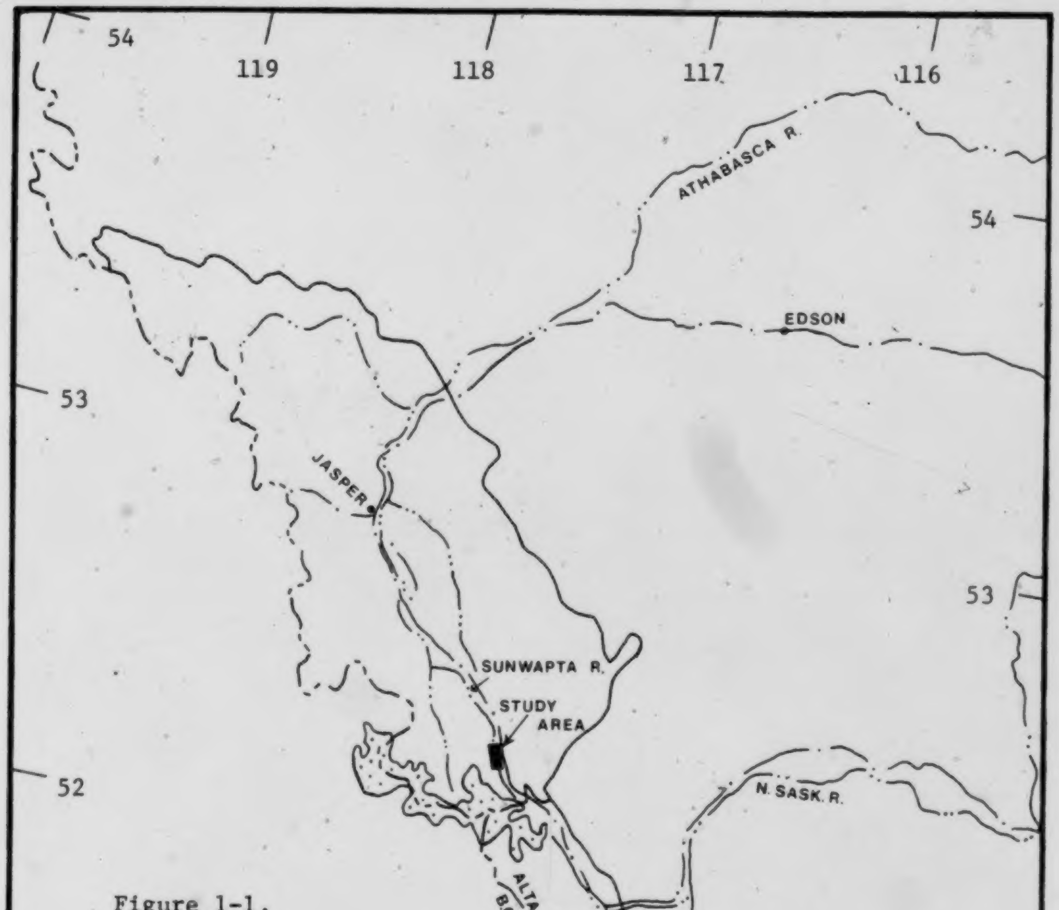
1.3.1 Location

The river chosen for this study is the Sunwapta, located at the southern end of Jasper National Park in western Alberta. The river is approximately 50 km in length, joining with the Athabasca River at Athabasca Falls. The uppermost 20 km of the river is discontinuously braided, flowing through gravelly outwash deposited proglacially. The lower 9 km of the upper 20 km constitutes a continuous stretch of braided gravel flats known locally as Beauty Creek Flats. These gravel flats were chosen as the study area (figure 1-1, p. 8).

1.3.2 Climate

The climate of the region (Canadian Rocky Mountains) has been described by Heusser (1956) as continental in character. Heusser (tbl. 2, p. 268) presents the temperature and precipitation extremes from discontinuous records started at Jasper in 1916. At the time of publication of his paper the maximum and minimun recorded temperatures were 98 F° (36.6 C°) and -53 F° (-47.2 C°) in 1941 and 1916 respectively. The maximum and minimum precipitation was 22.78 in. (57.86 cm) and 8.47 in. (21.51 cm) in 1948 and 1941 respectively. Maximum and minimum snowfall was 80.9 in. (205.49 cm) and 19.7 in. (50.04 cm) in 1953 and 1952 respectively. Complete precipitation records for 1971 through 1974 for the Columbia Icefields station located approximately 121 km from Jasper show an increase from 78.28 cm in 1971 to 115.44 cm in 1974, suggesting that an increase in annual precipitation has occurred since the publication of Heusser's paper.

During the summer of 1977 when this investigation was undertaken the weather was mainly cold and rainy. Longer periods of warm and clear weather began during the first half of August when most of the data was collected. Figure 1-2 presents the daily mean discharge, average temperature


54
119
118
117
116
ATHABASCA R.
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EDSON
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JASPER
53
SUNWAPTA R.
STUDY
AREA
52
N. SASK. R.
ALTA.
B.C.
52
51
BOW R.
BANFF
51
river
major highway
park boundary
columbia icefields
provincial boundary
0
20
40
SCALE IN KM
118
117
116
115
50

Figure 1-1.

Sunwapta River, Jasper National Park, western Alberta; see figure 1-3 for enlarged view of study area.

and average per cent cloud for the gauging station established at the top end of Beauty Creek Flats for the period July 21 to August 15, 1977.

1.3.3 Physiography

The Sunwapta River along Beauty Creek Flats has a valley width of approximately 0.5 km. It is bordered on the east by Mt. Sunwapta and Tangle Ridge at approximately 3350 m and 2900 m respectively. On the west are mountains of slightly smaller size. The valley walls are heavily treed from the level of the gravel flats to the tree line and display avalanche scars. The braided gravel flats, properly termed a valley train (the equivalent Icelandic term is dalsandur ; Church, 1972, p. 4) are at an approximate elevation of 1550 m. Mt. Athabasca and the Columbia Icefields are visible to the south and the linear trend of mountains known as the Endless Chain lie along the east side of the valley to the north, out of the study area.

1.3.4 Surficial And Bedrock Geology

Neither surficial nor bedrock geology were investigated in any detail as they did not relate to the topic of the investigation. Inspection of aerial photographs suggest that the valley walls may be veneered with lateral moraine remnants but this was not corroborated by field work. Along the south end of Beauty Creek Flats buff coloured limestone and shaly to silty limestone outcrops were noted at several

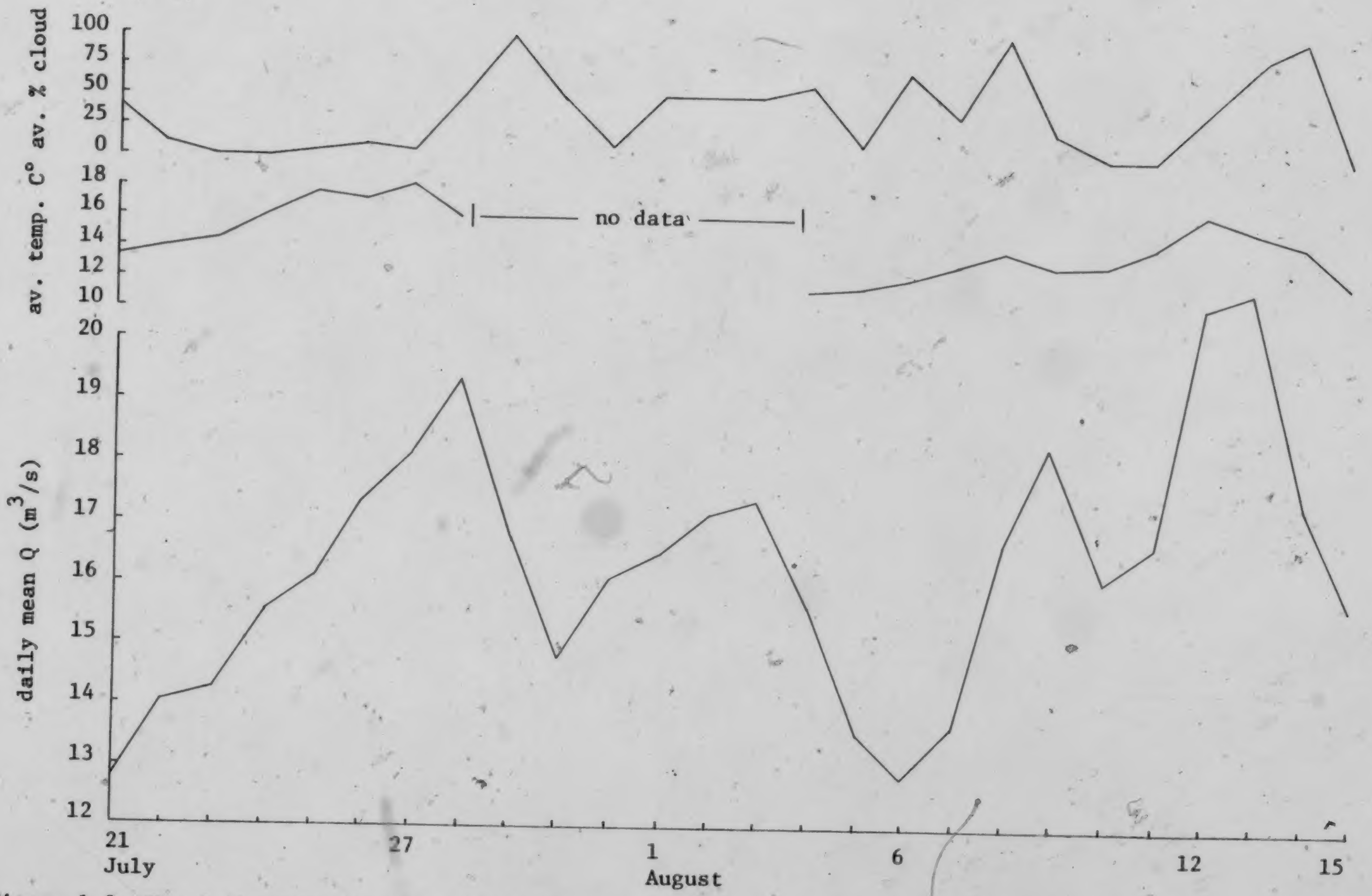


Figure 1-2. The daily mean discharge, average temperature and average percent cloud cover for the period July 21 to August 15, 1977 from the gauging station at the top of Beauty Creek Flats.

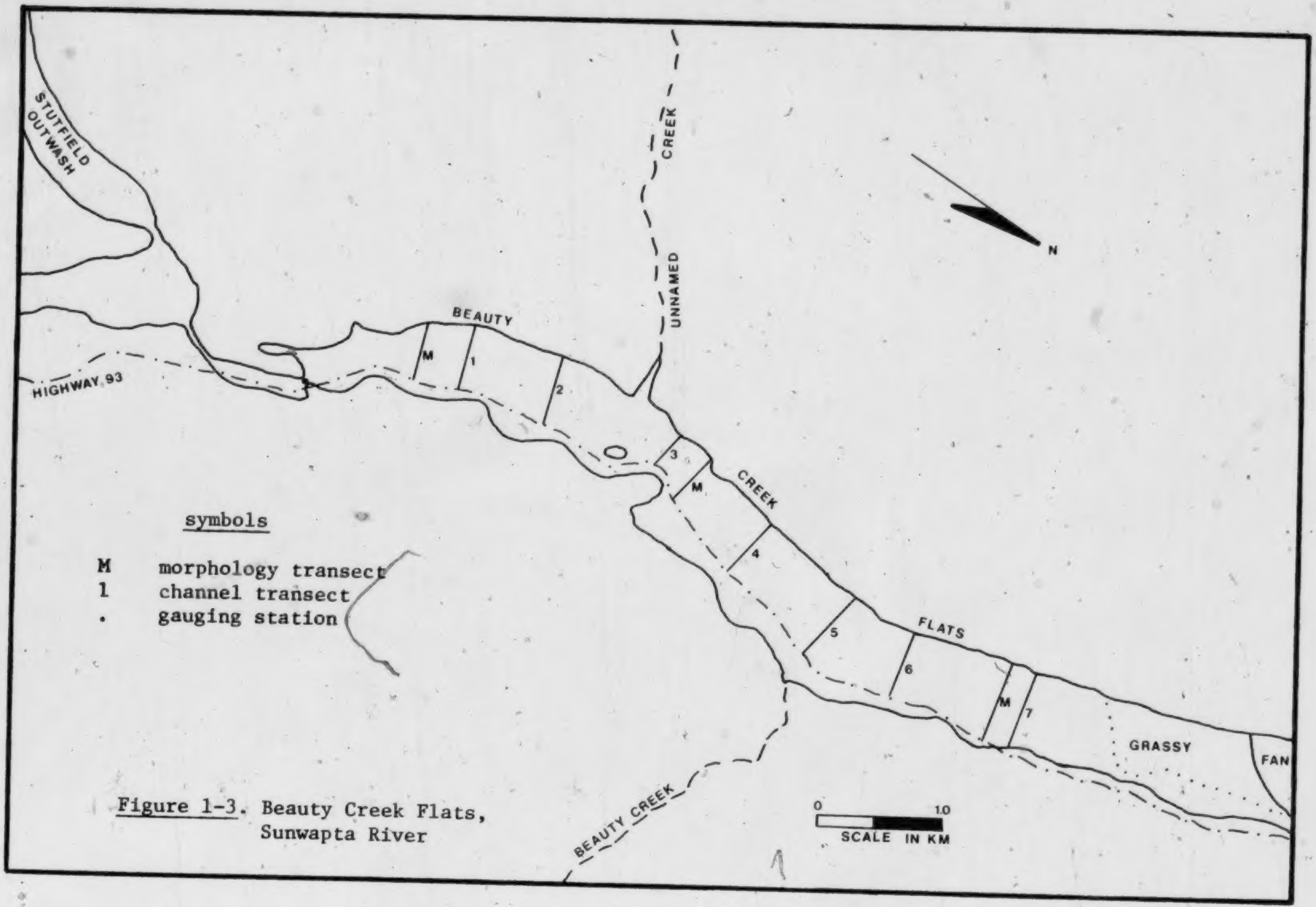
locations adjacent to the valley train. In one instance silty limestone outcropped as a small island in the gravelly alluvium.

1.3.5 General Description

The Sunwapta River is proglacial. Its meltwaters are derived principally from Athabasca and Dome Glaciers located approximately 20 km south of Beauty Creek Flats. They are outlet glaciers of the Columbia Icefields. Within the upper 20 km the Sunwapta River receives additional discharge contributions from Stutfield Glacier and an unnamed creek joining the river from the west and from Tangle Creek and Beauty Creek which join the river from the east. The former two contribute meltwater while the water of the latter two is derived from snowmelt and pluvial runoff. The unnamed creek and Beauty Creek join the Sunwapta within the study area (see figure 1-3, p. 12).

A meandering regime exists on the braided channel network of the gravel flats. As a consequence of this, the area of active channels shifts from west to east from the upper (south) to the middle and lower (north) reaches respectively. The areas of inactive channels adjacent to the active channel areas have been partially stabilized by grassy vegetation. Small patches of stunted or infant softwood occur in some of the stabilized areas.

Three transects were surveyed on Beauty Creek Flats in order to delineate the various morphological units of the


STUTFIELD OUTWASH
HIGHWAY 93
BEAUTY
CREEK
FLATS
UNNAMED
CREEK
BEAUTY CREEK
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7
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1.0
SCALE IN KM
symbols
M morphology transect
1 channel transect
. gauging station

Figure 1-3. Beauty Creek Flats, Sunwapta River

valley train. The transects were located at 1.3, 3.3 and 6.4 km from the southern end of Beauty Creek Flats and are shown on figure 1-4 A, B and C on p. 14 and 15. The morphological units have been given an identifying number, keyed to the following scheme:

1 - active channel area

2 - stabilized area of inactive channels

3 - active channel

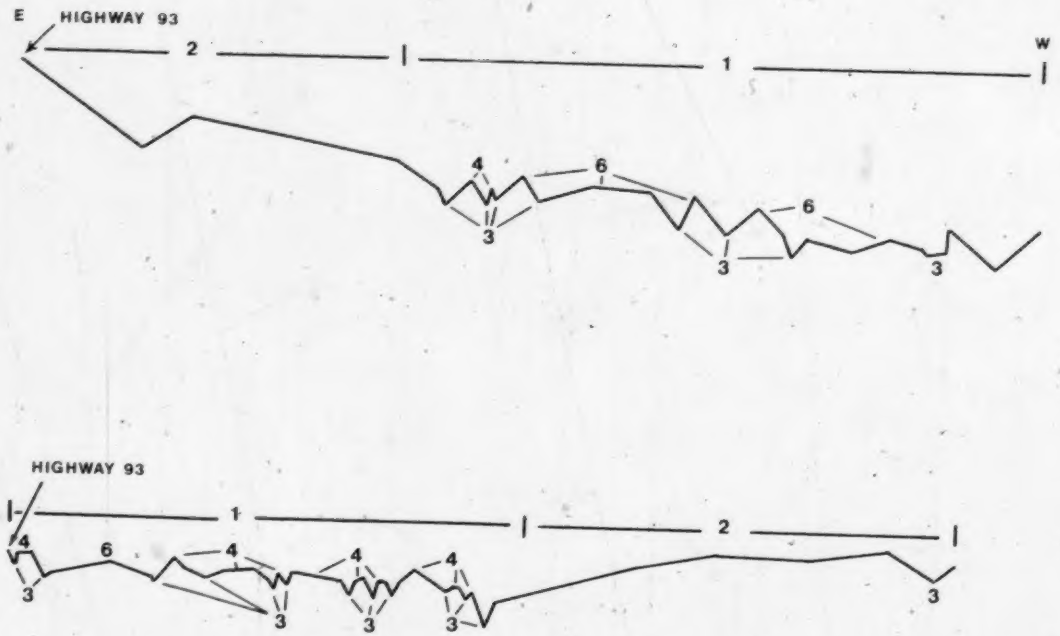
4 - braid bar, major or minor

5 - non-stabilized area of discontinuous channels and standing water

6 - interchannel area

The paucity of active channels is a function of the time of the year the transects were surveyed (early June). As observed in the field the morphological units are gradational with each other.

A longitudinal profile was established by levelling the water surface slope of the dominant active channel (see figure 1-5, p. 16). The marked decrease in slope downstream is attributed to an alluvial fan located at the northern end


E
HIGHWAY 93
2
1
W
4
6
3
6
3
3
HIGHWAY 93
4
6
4
4
4
3
1
2
3
3
3
3

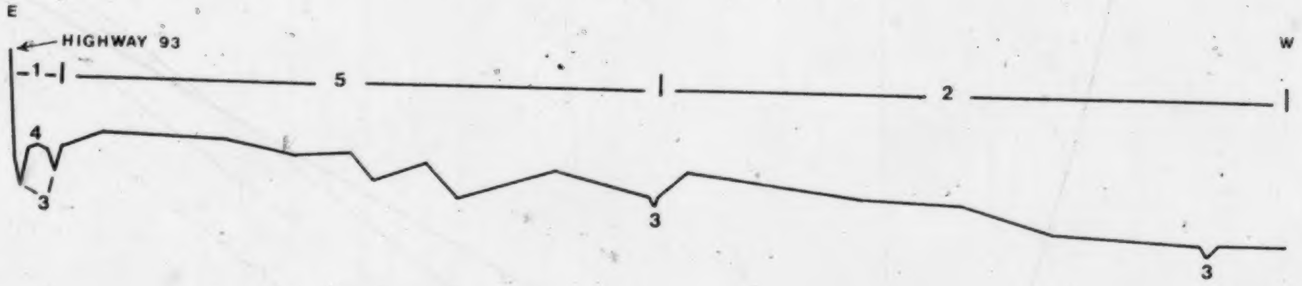
A June 6, 1977

B June 5, 1977

horizontal scale 1:3100

vertical exaggeration = 31

Figure 1-4 A and B. Upper and middle reach morphology transect; for explanation of numbers see page


E
HIGHWAY 93
1
5
2
W
4
3
3
3

horizontal scale 1:3100

vertical exaggeration = 31

Figure 1-4 C. Lower reach morphology transect, June 5, 1977; for explanation of numbers see page

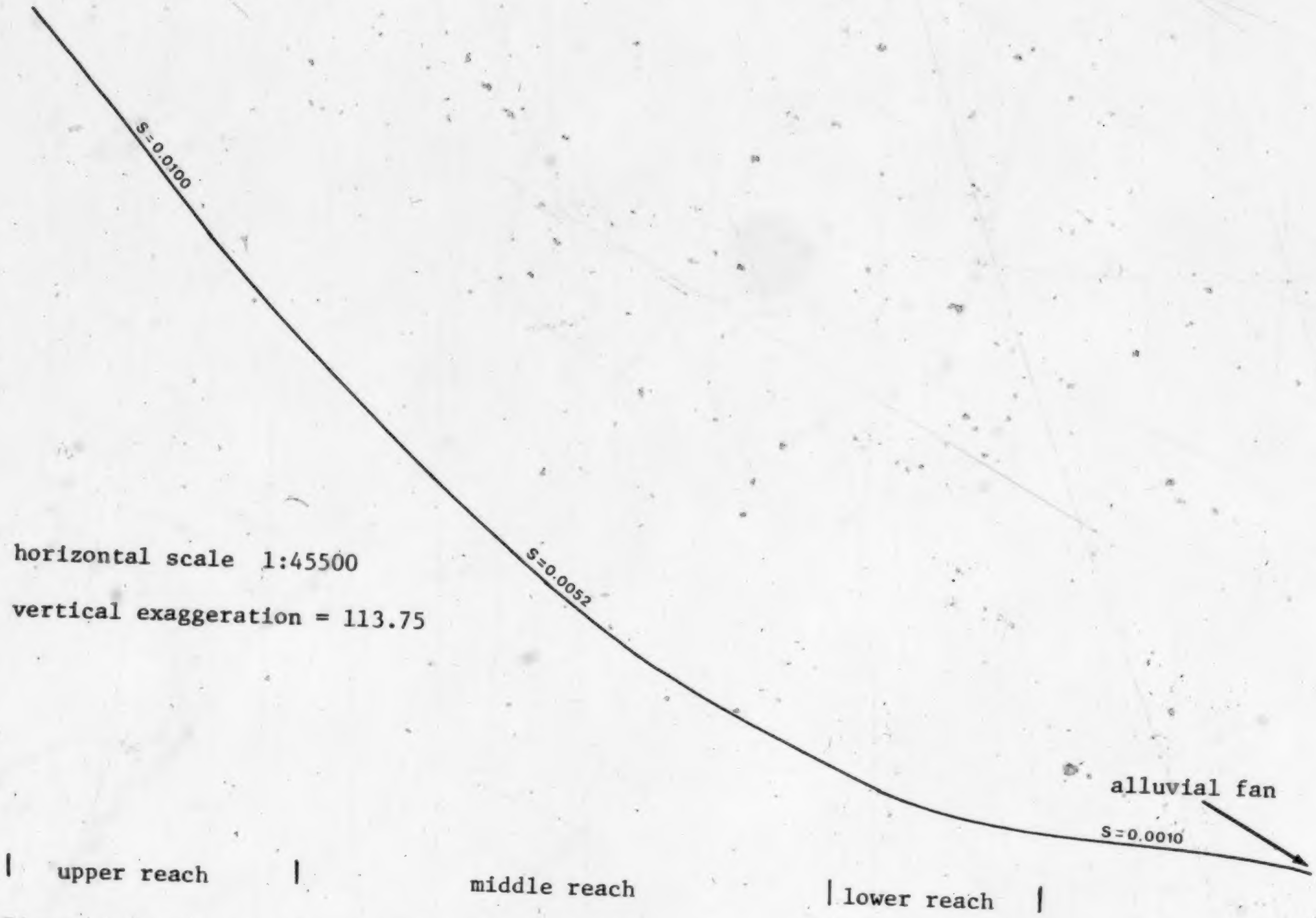


Figure 1-5. Water surface slope along the dominant active channel on Beauty Creek Flats.

of Beauty Creek Flats. The fan constricts the river to a single channel and creates a local base level for the channels of the study area. Within approximately 2 km upriver of the fan (below the lower reach of this study) the channels are bedded with coarse sand to fine gravel and from eighty to ninety percent of the valley width consists of grassy stabilized alluvium (see figure 1-3). As a consequence of this decrease in slope there is a corresponding decrease in the grain size of the alluvium downstream. The valley train sediment is dominated by coarse to fine gravel with sand occurring principally as interstitial grains, less frequently as small irregular pockets and lensoid bodies and rarely as thin discontinuous strata within the gravel.

As shown on figure 1-3, highway 93 (the Icefields Parkway) runs across the eastern margin of Beauty Creek Flats. The highway serves as a constraint on fluvial activity and restrains the amplitude of the migration of the areas of active channels. In addition, dykes composed of very coarse rip-rap have been placed at regular intervals along the road projecting obliquely onto the valley train. These prevent undercutting of the road by interrupting the lateral migration of individual channels. Inspection of pre-highway 93 aerial photographs show that its construction has caused the following:

1. shifting of the areas of active channels
2. a reduction in the width of the participating valley

train by sealing off the eastern marginal area of Beauty Creek Flats

An increase in the total discharge being conducted by the braid channels occurs at the interface between the upper and middle reaches where the discharge of the unnamed creek enters the Sunwapta River. This is meltwater derived from a small unnamed valley glacier and is thus opaque with rock flour. A second increase in the total discharge on Beauty Creek Flats occurs where Beauty Creek joins with the Sunwapta. This defines the start of the lower reach. In contrast with the unnamed creek, the water of Beauty Creek is clear, being derived principally from snowmelt and pluvial runoff.

Plates 1 through 12 (p. 19 - 24) show the upper, middle and lower reaches of Beauty Creek Flats and previously mentioned salient features of the study area.

Plate 1: A view looking west at the lowermost portion of the upper reach in April, 1977. Ice and snow is still present in some of the channels.

Plate 2: A view looking south up the upper reach during a high flow period. Note the barely submerged bar in the center foreground.

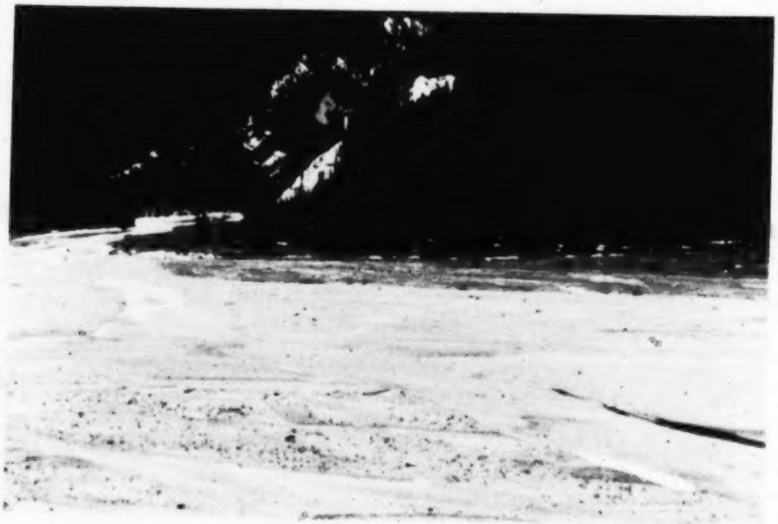


Plate 3: A westward view at the uppermost portion of the middle reach in April, 1977. Note the very low flow in some of the channels and the inactive, stabilized western margin of the valley train.

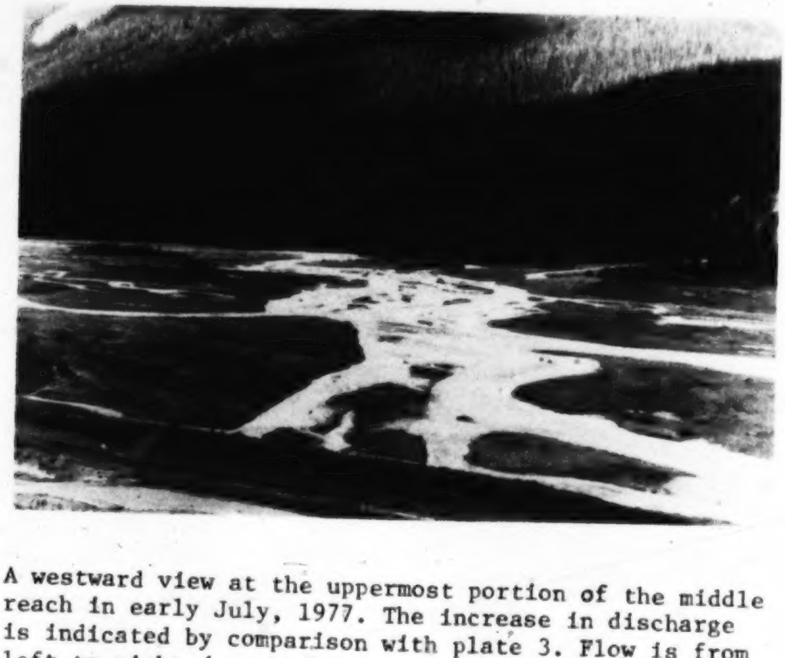


Plate 4: A westward view at the uppermost portion of the middle reach in early July, 1977. The increase in discharge is indicated by comparison with plate 3. Flow is from left to right (northward).

Plate 5: A northward view down the middle reach in July, 1977. Highway 93 is in the foreground.

Plate 6: A northward view down the lower reach in mid-summer, 1977. The photo was taken from highway 93.

Plate 7: A view of the gorge cut through silty limestone by the unnamed creek on the western side of Beauty Creek Flats. This creek marks the beginning of the middle reach.

Plate 8: A view of discharge from Beauty Creek mixing with the flow on Beauty Creek Flats. This marks the beginning of the lower reach.

Plate 9: Aeolian loess transport (center of photo) on the middle reach of Beauty Creek Flats on a gusty day. Note the small breach in the dyke in the foreground.

Plate 10: Avalanche scars on the western valley wall of Beauty Creek Flats.

Plate 11 : A southward view from highway 93 of the grassy area (right center of photo) located below the lower reach of Beauty Creek Flats (see fig. 1-2). The channel in the foreground is bedded with coarse sand and fine gravel.

Plate 12 : The center portion of the treed alluvial fan at the bottom of Beauty Creek Flats. The grassy area in the center of the photo is an abandoned channel on the fan.

2. Developments In The Hydraulic Geometry Approach To Channel Change

2.1 Introduction

Since the concept of hydraulic geometry was first introduced by Leopold and Maddock (1953), it has become one of the most intensively investigated areas in fluvial geomorphology (Thornes, 1977, p. 91). The literature dealing with it is multi-disciplinary with contributions from fluvial geomorphology, river engineering and sedimentology. Rhodes (1978, p. 194) states that at least 587 sets of hydraulic geometry exponents have been computed. No attempt is made here to provide a comprehensive review of this literature, rather a discussion of important developments in the hydraulic geometry approach to channel change that have resulted from the many publications is presented.

2.2 Two Schools Of Thought

One of the most significant developments concerning hydraulic geometry and channel change involves the evolution of two schools of thought concerning the manner in which the hydraulic geometry relations of a particular river or physiographic or climatic region are dealt with. Leopold and Maddock's paper in which hydraulic geometry exponents were averaged for seven river basins initiated a school of thought which searched for uniformity in channel response from among different physiographic and climatic regions.

Subsequent papers such as that by Leopold and Miller (1956) and by Wolman (1955) served to support this approach. As Park (1977, p. 134) states, a preoccupation of subsequent studies has been to show how closely their exponents compare to the average values for the mid-western United States determined by Leopold and Maddock. In 1964 this principle gained further support in Leopold, Wolman and Miller's text entitled Fluvial Processes in Geomorphology which has become a standard reference.

A second and opposing approach is represented in two recent publications, by Rhodes (1977) in which 332 sets of hydraulic geometry equations were utilized and by Park (1977) wherein a global variation in hydraulic geometry equations is examined. Rather than emphasize only the average relations for a river or region and in so doing mask differences which exist amongst its stations or streams, respectively, Rhodes and Park underscore the variability amongst the exponents from different stations on the same river, between rivers, or from different physiographic and climatic regions. They stress the need to avoid averaging and to start concentrating on providing an explanation for the local variations in the values of the hydraulic geometry exponents. In conjunction with this they also stress the provision of detailed descriptions of local conditions at the time of data acquisition.

In this investigation the latter school of thought is followed. The emphasis is on providing an explanation of the downstream variation in channel response. This approach is supported by Knighton (1975) who demonstrated that short term temporal changes in channel morphology can occur at a given channel cross section during flow measurements which constitute a major source of scatter in a plot of a hydraulic geometry relation for this section.

2.3 General

Recently there has been criticism of the conceptual background involved in the conventional hydraulic geometry approach to channel change. It was mentioned in section 1.1 that the conventional approach of hydraulic geometry studies involved the use of the power function (log-linear plot) to express the relationship between the dependent and independent variables. The ability of such a straightforward approach to interpret and forecast channel change has been questioned by several authors (Thornes, 1970; Richards, 1973, 1976). The assumptions involved in the conventional approach were discussed by Knighton (1977, p. 101) and are as follows:

1. Discharge (Q) is the dominant independent variable to which the dependent variables adjust and by which other independent variables (such as grain size of bed material) are controlled to varying degrees.
2. Power functions are suitable expressions of the hydraulic geometry relationships.
3. A given set of relations represents the mean condition

of stream behaviour at a given cross section.

An excellent discussion of the conceptual problems involved in the use of this approach was given by Thornes (1977, p. 91-100).

Although the conventional hydraulic geometry approach to channel change is usually limited in its interpretative and predictive abilities by such conceptual difficulties it has been and is still accepted as a suitable means of analysing the behavioural characteristics of natural streams (Knighton, 1977, p. 101). The applicability of these difficulties to this study is discussed in section 4.2.4.

Additional salient papers concerning channel change are those of Schumm (1960, 1968, 1969) which emphasize the role of bank and bed sediment properties in determining how a channel will respond to an imposed discharge. Schumm has also recently (1977) published a text in which channel changes are dealt with.

Langbein (1964) presented his minimum variance theory in which the most probable, conservative values of the hydraulic geometry exponents are statistically derived.

3. Data Acquisition

3.1 Equipment Used

Levelling and the determination of flow velocities with current meters were the major field operations in this investigation. The former provided the means of obtaining accurate information on channel dimensions (length, cross section morphology) as well as being used for the long profile and morphology transects of the valley train (refer to figures 1-5 and 1-4, respectively). Information on flow velocity was acquired by the use of current meters attached to wading rods. Flow velocities were obtained both as primary data and for combination with cross sectional area for some of the discharge values presented in this report. Two types of current meters were used. A Price type AA current meter was used when depths exceeded 0.31 m (1 ft) and a pygmy current meter was used when the depth of flow was less than 0.31 m. Some of the ancilliary equipment consisted of stopwatches, shovels and buckets (for channel sampling), measuring tapes and a Stevens type F stage recorder. Plates 13 and 14 on p. 30 illustrates one of the current meters and the level used.

Plate 13: Field assistant with a Price AA current meter at the gauging station at the top of Beauty Creek Flats, June, 1977.

Plate 14: A photo of the level used for the field work taken on the upper reach of Beauty Creek Flats in June, 1977. Highway 93 is in the background. The flow is from right to left.

3.2 Flow Conditions At The Time Of Data Acquisition

The data on channel morphology and hydraulics for the three reaches of Beauty Creek Flats were obtained during the first two weeks of August, 1977 (Aug. 4-15), when the summer peak discharge period occurred. Since the data were obtained throughout the day the diurnal discharge variation was significant. In this context, the time of day (implying rising or falling stage) was recorded for each set of channel data obtained. During data acquisition the stage varied from slightly below bankfull (usually pre 10 A.M.) to bankfull (usually 6-9 P.M.). For this reason the adopted dominant discharge of this study is bankfull discharge. The discharge in the braid channels of Beauty Creek Flats during the preceeding part of the summer had not reached bankfull conditions (except occasional brief periods of 1-3 days) although considerable variation in stage had occurred associated with varying weather conditions. As has been observed for other proglacial rivers, a prolonged period of both clear and hot weather (5-6 days) are required before maximum discharges occur. For the Sunwapta River at Beauty Creek Flats there was a 1.5 - 2.0 day lag between a change in weather and a noticeable braid channel response.

Measurements of bed load transport were not attempted for the Sunwapta braid channels ; however it was noted that significant gravel transport did occur throughout the majority of the approximately two week period during which the data were obtained. It was not always possible to see such transport since the rock flour in suspension obscured visibility. The transport of sediment was noted by either feeling the collisions with a pole held in the water against the bottom or by hearing collisions during movement. Significant gravel transport was not noted at any previous time during the summer; however, transport of sand sized detritus occurred at varying rates throughout the summer depending on the weather controlled discharge conditions. During the data acquisition it could be seen that the most active braiding was occurring in the middle reach. At this time it was also noted that the major source of coarse detritus was upstream bank collapse. As the interstitial fines are washed out, the heavier gravel collapses into the flow. The downstream transport distance of coarse detritus supplied in this manner has been determined by other investigators to be in the order of hundreds of meters per flood season (Butler, 1977, p. 1072).

Samples of the suspended load being carried by the channels during the time of data acquisition were not obtained ; however, it was felt that the maximum suspended load conditions encountered occurred at this time.

Water temperature varied considerably between the upper and lower reaches of Beauty Creek Flats. The average temperatures of the active channel water in the upper, middle and lower reaches were 6.28, 8.05 and 9.20 C°, respectively.

Unfortunately the total discharge carried through the middle and lower reaches during this time is not known since the volume of water contributed by the unnamed creek and Beauty Creek (see figure 1-3, p. 12) was not monitored. However, the total discharge in the upper reach during this period can be estimated from the records of a gauging station established at the head of Beauty Creek Flats where the flow was constricted to a single channel by what appeared to be a bedrock protrusion from the western valley wall. Plates 15 and 16, p. 34 and 35 present different views of the gauging station and the stage recorder apparatus.

The discharge entering the upper reach during August 4-15, 1977 varied between 13-21 m^3/s. These values were obtained from a stage-discharge relation established for the station from eleven discharge measurements acquired between June 18-26, used in combination with the stage recorder chart of the data acquisition interval. The stage-discharge relation, referred to as the rating equation is

$$Q = 27.9\ S^{0.91} \qquad r^2 = 0.97 \qquad \text{Eq. 3.1}$$

where Q is water discharge (m^3/s) and S (m) refers to river stage. Figure 3-1 presents the graph of this relation. The derived discharge range for the upper reach should only be treated as a good estimate due to the following limitations arising out of the derivation of the rating equation.

1. The eleven discharge values used in the derivation of

Plate 15: A downstream view of the gauging station established at the top of Beauty Creek Flats. The stilling well is shown in the center of the photograph. The channel is approximately 12 m wide.

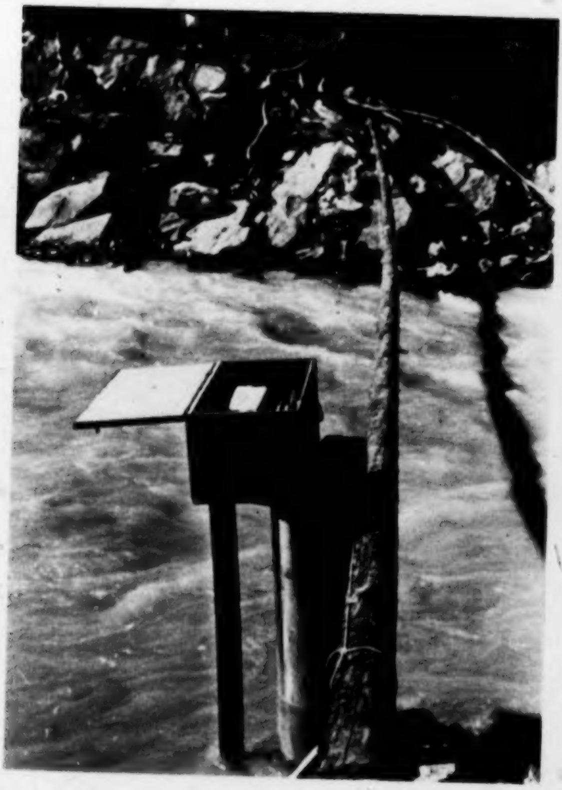


Plate 16: A view of the Stevens stage recorder contained within the box attached to the top of the stilling well.

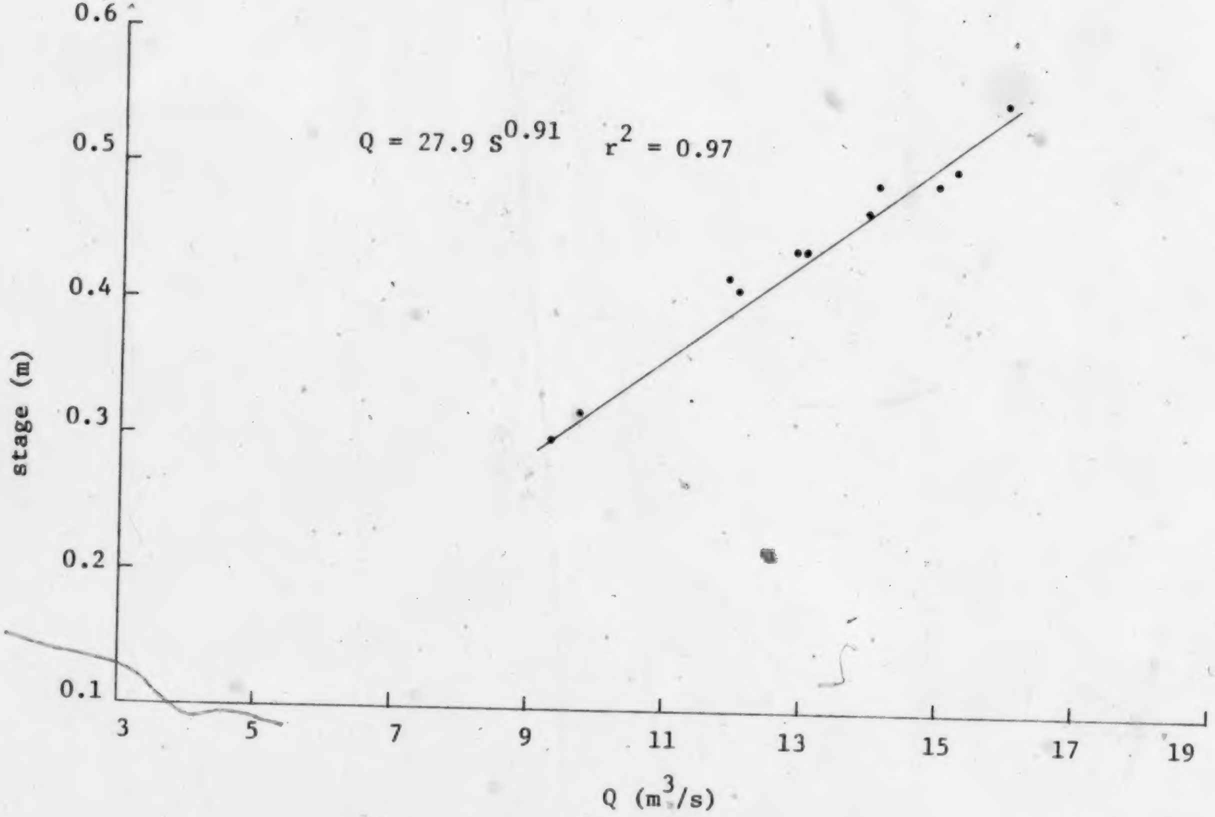


Figure 3-1. The suggested stage - discharge relation for the gauging station established at the top end of Beauty Creek Flats, Sunwapta River. The data was acquired from June 18-26, 1977.

the relation represent a mixture of rising and falling stage measurements. Equation 3.1 represents an estimated steady state relationship for this data.

2. Although an assumption of no standing pools of water (zero stage) at zero discharge would seem to be reasonable due to the coarseness of the bed material no measurements below 9 m^3/s were obtained, thereby forcing this assumption.
3. The maximum discharge used in deriving the relation was approximately 16 m^3/s. To determine the higher discharges prescribed for the upper reach a log-linear extrapolation of the rating curve is required. There is no evidence to suggest that the relation would behave linearly at the higher stages associated with the larger discharges and in many instances rating curves are found to curve upward at these stages.
4. Practicality forced the establishment of the gauging station just above a bend in the channel (see plate 15, p. 34). The backwater effects found at such a location would slightly amplify the stage measurements recorded.
5. The Stevens stage recorder was not operating at the gauging station until July 21. The stage measurements made prior to this, those used in the derivation of the rating equation, were done by eye using a levelling rod and slight inaccuracies may have been introduced.

A section of the stage recorder chart covering the period August 5-10 is presented as figure 3-2, p. 39. Two features of the stage fluctuations during this period are to be noted.

1. The period August 5 to mid-day August 7 clearly demonstrates a pattern of very rapid rise in stage from late morning to late afternoon followed by a slow fall in stage from the day's maximum to the late morning of the subsequent day. This type of pattern is characteristic of proglacial rivers during periods of clear hot weather and demonstrates how quickly the source glaciers can respond to solar heating.
2. At approximately 12:30 A.M. on August 9 a sudden increase in stage occurred which lasted approximately 2.5 hrs., peaking at 3:00 A.M., whose maximum stage exceeded the previous day's maximum. Although not shown in figure 3-2 a similar burst occurred between 2 and 3 A.M. on the morning of August 12. These bursts occurred subsequent to several days of clear hot weather and are interpreted as representing the passage of flood waves originating in some sort of plumbing burst in the upstream glaciers which occurred during the previous day of clear, hot weather.

Although the unnamed creek and Beauty Creek were not monitored visual comparison of their flow magnitudes to that of the gauging station during August 4-15 suggested that their discharges individually, may approximate that of the gauging station. This being the case, a guess at the range of total discharge on Beauty Creek Flats during this period

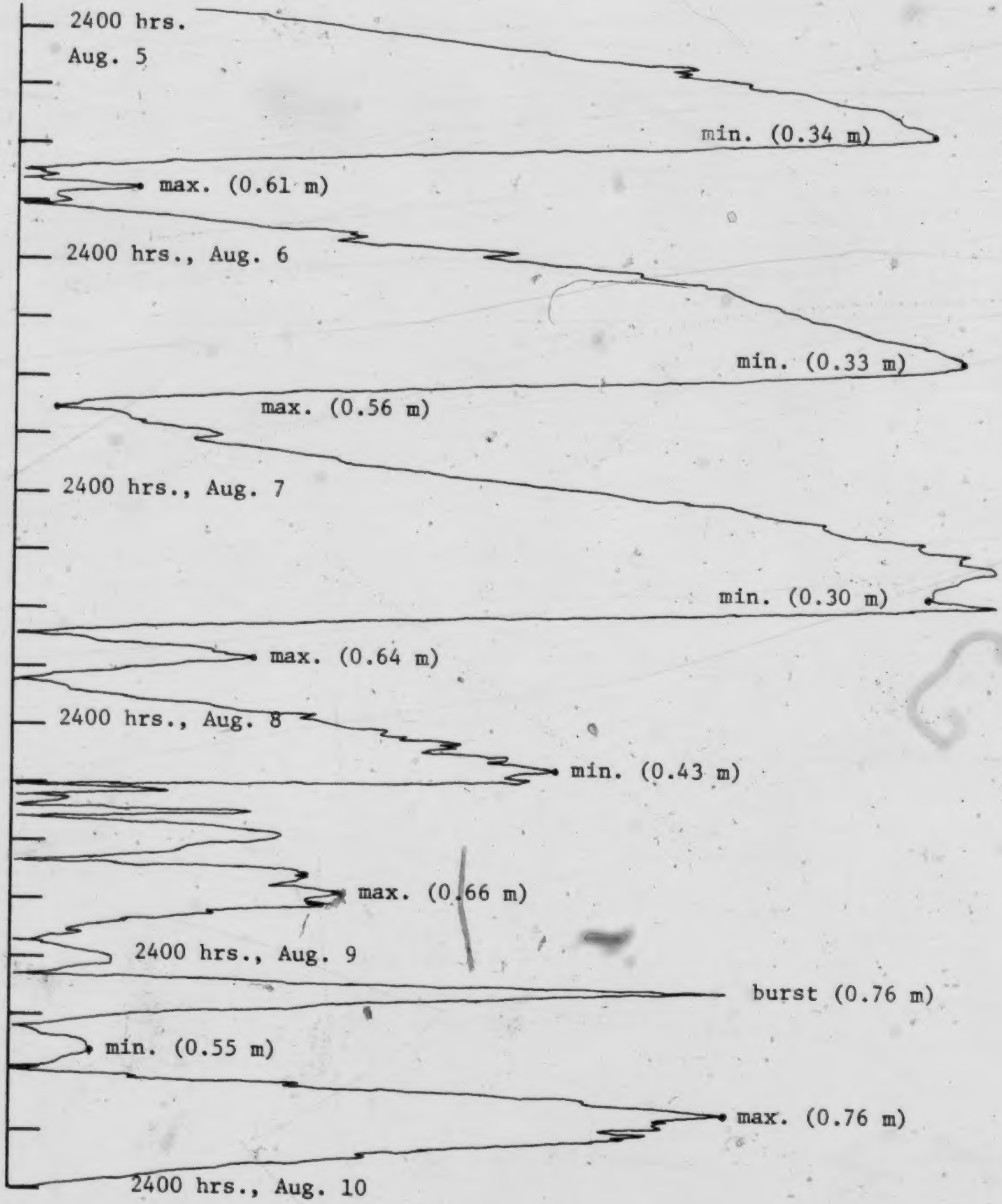


Figure 3-2. The stage recorder chart for the period August 5-10, 1977. Daily maximum and minimum stage is indicated by dots on the graph. The time scale increments are 6 hrs.

would be 39-63 m^3/s, assuming that infiltration on the valley train was not significant. This assumption is considered to be reasonable. Calculations of Church (1972, p.25) for the outwash detritus of Ekalugad Fiord show the groundwater discharge at this site to be approximately 0.4% or less of the mean discharge across the gravel flats.

3.3 Methodology

To facilitate the realization of the first two objectives outlined on p. 6, Beauty Creek Flats was separated into an upper, middle and lower reach from each of which data on channel morphology and flow conditions would be obtained and then compared. In so doing, the first objective is realized by simply combining the morphology and flow data of the three reaches. As previously indicated, the upper reach is defined as extending from the gauging station location up to but not including the point at which the unnamed creek enters the valley train, a distance of approximately 2.0 km (see figure 1-3, p. 12). The middle reach extended from this position to a position located at approximately 5.73 km from the beginning of Beauty Creek Flats, a location just above the confluence of Beauty Creek with the valley train. The lower reach extends from this point to a point at 7.19 km down the valley train. As mentioned previously, the last approximately 2 km of the valley train were not included in the lower reach since the channels of this area are predominantly sand bedded and have vegetated, stabilized banks, which would cause their behavioural characteristics to contrast sharply with those of the gravelly, non-cohesive bed and bank material of the channels chosen from the lower, middle and upper reaches.

The three reaches of Beauty Creek Flats are basically similar with each containing areas of active as well as inactive channels (see figure 1-4 A, B and C, p. 14 and 15). The principle difference in terms of acquiring channel data is the number of active channels encountered in each reach. The number of active channels in each reach during the data acquisition period was never actually counted ; however a marked increase occurred in passing from the upper to the middle reach with only a slight increase occurring in the lower reach relative to the middle reach. Plates 2, 5 and 6 (p. 19 and 21) should be referred to for a visual impression of each reach.

In the context of the objectives presented on p. 6, it was desirable to obtain as much information on channel morphology and hydraulics as manpower and time would permit. In order to accomplish this two groups of data were collected, each of which contained morphologic and hydraulic information on the active channels of the upper, middle and lower reach. The two groups are primarily distinguished by the manner in which their discharge values were determined. Discharges of the first group were determined using current meter flow velocity measurements acquired in the field. This group of data is referred to as the measured discharge data set. Discharges for the other group of channel data were determined theoretically using morphologic and bed material grain size information from the channels. This group is referred to as the theoretical discharge data set. The relation used for the discharge calculation is presented in the subsequent section. It is to be noted that the channels of each group are unique; ie. the same channel was not investigated twice. The main reason for separating the field data into two groups was the amount of time consumed in making numerous current meter discharge measurements with only two people involved. For each group the channels selected from the upper, middle and lower reaches had to meet the following criteria to ensure that their adjustments to the imposed discharge were representative of unrestricted channel change in coarse, non-cohesive bed and bank alluvium.

1. A Well Defined Channelized Flow

   There were many occurrences of vaguely linear sheets of water flowing on sub-aerial bar tops and in interchannel areas which were rejected since there was no evidence of channelization associated with them.

2. Unrestricted Lateral Migration Potential

   Active channels which flowed for all or part of their length against the roadside dykes or in areas in which the bank material is to varying degrees stabilized by vegetation were not included in the investigation.

In order to secure a representative sample a wide range of channel sizes was included in each group of data. To obtain the morphologic and hydraulic information a data acquisition format was established for each group of data and applied to the channels chosen for inclusion in one of the two groups. The format for each group is presented below.

Measured Discharge Data Set

Thirty channels, ten from each of the upper, middle and lower reaches were randomly selected and investigated in the following manner:

1. Once a suitable channel was located a 30.5 m (100 ft) stretch of the channel was measured off and marked by placing wooden stakes in the gravel on the banks adjacent to the start and finish.
2. Using driftwood floats and a stopwatch, three thalweg surface velocities were determined by timing the floats placed in the thalweg over the 30.5 m distance.
3. At 0, 15.2 and 30.5 m thalweg velocity at 0.6 of the flow depth (from the surface down) was recorded through the use of either the AA or pygmy current meter. If depth exceeded 0.46 m (1.5 ft) the velocity at 0.2 and 0.8 of the depth was obtained and averaged.
4. A velocity-area (discharge) measurement was obtained

from a flow cross section located at the midpoint of the channel length (length was defined by either a bifurcation and/or a confluence). This was achieved by staking a rope across the flow, measuring the width and using loosely tied short lengths of flagging tape to indicate the position of the verticals at which current meter velocity measurements were taken. The spacing of the verticals was dictated by channel width and by attempting to follow a well established rule of thumb which suggests that accuracy is maintained if the discharge between adjacent verticals is kept less than 10% of the total discharge of the cross section.

Once the velocity-area measurement was completed the equipment was gathered up and another channel was sought where the procedure would be repeated. For each channel the float velocities of step 2 were averaged as were the current meter velocities of step 3, giving an average thalweg surface velocity and an average thalweg velocity at 0.6 of the flow depth, respectively. These two averages were then combined to give an average velocity at 0.6 of the flow depth to average surface velocity ratio. This ratio was averaged (0.78) for the thirty channels of this data set and used to calculate the average velocity at 0.6 of the flow depth for the channels of the theoretical discharge data set in which only float velocities were determined (see below). Also, the average of the ratio of average surface velocity to average cross section velocity was determined (1.67) for the calculation of the average cross section velocities of the theoretical discharge data set which are used in the determination of the value of Mannings n (roughness).

Theoretical Discharge Data Set

Thirty channels, ten from each of the three reaches were chosen for this group. Rather than picking the channels at random from throughout a reach as was done for the channels of the measured discharge group, seven transects (numbers 1 and 2 in the upper reach, numbers 3, 4 and 5 in the middle reach and numbers 6 and 7 in the lower reach ; see figure 1-3) were walked across the valley train. Along each of these, intersected, qualifying active channels were investigated in the following fashion:

1. Using the level and levelling rod the channel length, water surface slope and bed slope were determined along the channel centerline.
2. An upper, middle and lower flow cross section were levelled (the middle cross section was not always obtainable).
3. The water temperature was recorded.
4. At or near the thalweg of the middle cross section a grab sample of the bed material was obtained with a shovel and bucket. Loss of a large amount of the fines was unavoidable with this technique. The effect on the grain size distribution is discussed in the next

chapter.

5. The average thalweg surface velocity was determined by averaging the times obtained from placing five floats in the thalweg and allowing them to travel the length of the channel.

As mentioned earlier, the discharge of each of these thirty channels was determined theoretically using the morphologic and grain size information obtained in the above manner in a relation to be described in detail in the subsequent section. The average velocity at 0.6 of the flow depth was obtained for each channel by applying the average velocity ratio determined for the channels of the measured discharge data set to the average thalweg surface velocities.

The channel data obtained in the three reaches of Beauty Creek Flats according to the two formats described above are presented in tabular form as tables A-1 and A-2 on p. 130 and 132 respectively, of appendix A. Included in these tables are some additional morphologic and hydraulic parameters derived from the field data. For the measured discharge data set (table A-1) the derived parameters are flow area, width to depth ratio, Froude number and channel Reynolds number. The derived parameters of the theoretical discharge data set (table A-2) are flow area, average width, average depth, average width to depth ratio, average velocity at 0.6 of the flow depth, average bottom shear stress, Froude number, channel Reynolds number, Manning's total roughness parameter, n, and of course water discharge. The standard equations for the derivation of the hydraulic parameters are presented in appendix A.

3.4 The Theoretical Discharge Relation

The relation used to determine the discharge for the thirty channels of the theoretical discharge data set was derived and its use suggested by Dr. G. Parker of the Department of Civil Engineering. The equation uses dimensionless depth and width along with two other parameters (see below) to provide a dimensionless discharge. From the dimensionless discharge a dimensional discharge is obtained by another relation (eq. 3.3). The equation is

$$\tilde{Q} = 4.97\, {d_c^*}^{1.70}\, S^{0.50}\, B^* \left(1 - \frac{2.23}{a} \right) \qquad \text{Eq. 3.2}$$

where $d_c^* = \frac{d_c}{D_{50}}$ = dimensionless corrected depth

$B^* = W/D_{50}$ = dimensionless width

W = channel width

d_c = corrected average depth for the flow cross section ; explained further below

S = channel gradient ; water surface slope (S_w) was used

a = aspect ratio = W/d_c

$\tilde{Q}$ = dimensionless discharge

D_{50} = 50th percentile of the grain size distribution

In order to determine the dimensional discharge for the hydraulic geometry relations the following equation was used (suggested by G. Parker).

$$\tilde{Q} = \frac{Q}{(R\, g\, D_{50})^{\frac{1}{2}}\, D_{50}^{2}} \qquad \text{Eq. 3.3}$$

where Q = water discharge

$R = \frac{(\rho_s - \rho_f)}{\rho_f}$ = 1.70 = apparent density of the sediment

with ρ_s = the sediment density (limestone density of 2.7 gm/cc was used) and ρ_f = the fluid density

g = gravitational constant

Equation 3.2 is based on Keulegan's 1938 logarithmic velocity distribution equation for turbulent open channel flow. This equation provided the average velocity for the entire flow cross section by approximating the cross sectional shape of the channel as rectangular. Parker's relation is essentially addressing the natural situation of sloping channel margins. Although the corrected depth (d_c) of the relation is a theoretical allowance for sloping rather than vertical channel margins, the relation is still not completely compatible with natural flow cross sections since it assumes depth to fall at the midpoint of the channel width (G. Parker, personal communication). The flow cross sections of the thirty theoretical discharge channels presented in appendix B clearly demonstrate that the average depth falls nearer to the deeper outside margin. The average depth value shown in table A-2 of appendix A, represents a channel average derived from the average depths of the measured flow cross sections located at the upper, middle and lower channel positions. Other than placing the average depth nearer to one margin rather than at the midpoint of the channel width these averages satisfy the definition of d_c since the distance down the channel margins were measured at each flow cross section (thereby incorporating sloping bank data into the calculations). For this reason the average depths of table A-2 may be considered as an approximation of d_c (suggested by G. Parker). These are then adjusted by chopping 3.5 of the channel depth off of either side of the cross section and recalculating the average depth (suggested by G. Parker). This has the effect of moving the position of the average depth for the flow cross section nearer to the midpoint of the channel width and thereby satisfying the definition of corrected depth as best as possible. The depths arrived at by this procedure are slightly greater than the field data averages shown in table A-2. Since two and sometimes three flow cross sections were measured per channel for the theoretical discharge data set the adjustment was made for each flow cross section and then averaged to arrive at the estimated corrected depth value for each channel.

To summarize, the determination of dimensionless discharge for the channels of the theoretical discharge data set through the use of eqs. 3.2 and 3.3 requires the use of a corrected depth value in equation 3.2. The discussion above explains how to adjust the average depth values of the field data to arrive at an estimate of d_c.

It has been stated that equation 3.2 is based on Keulegan's logarithmic velocity profile relation. In so doing one is assuming that a logarithmic velocity profile is strictly applicable to the channels of the theoretical discharge data set. An indication of how applicable this velocity distribution is to these channels may be determined by calculating the theoretical surface velocity of the thalweg using Keulegan's logarithmic velocity distribution relation and comparing this tc the empirical average surface velocity of the thalweg contained in table A-2 of appendix A (suggested by G. Parker). Keulegan's relation, when used to determine the surface velocity is

$$V_{st} = 2.5\, u_* \ln 30 \frac{d}{D_{90}} \qquad \text{Eq. 3.4}$$

where V_{st} = theoretical surface velocity

u_* = shear velocity = $(\tau/\rho)^{\frac{1}{2}}$ where τ is shear stress and ρ is fluid density ; τ_o = average bottom shear stress is substituted for τ

d = depth of flow

D_{90} = 90^{th} percentile of the grain size distribution

This technique was tried on several of the channels and it was found that there was a significant departure from a logarithmic velocity profile. As a consequence, since equation 3.2 was based on Keulegan's relation the thirty theoretically determined discharges required adjustment by a correction factor. Since nearly all of the theoretical surface velocities were larger than their empirical counterparts the correction factor defined as (suggested by G. Parker)

$$\lambda = V_s / V_{st} \qquad \text{Eq. 3.5}$$

where V_s = measured surface velocity from table A-2

λ = theoretical discharge correction factor

was usually less than unity.

The value of parameters used in equations for the calculation and correction of discharge values of the theoretical discharge data set (refer to equations 3.2 to 3.5) are presented in table A-3 of appendix A.

3.5 Laboratory Procedures

Laboratory analysis was limited to the sieving of the grab samples of the bed material acquired for the channels of the theoretical discharge data set in order to determine the grain size distribution for each sample. The following procedure was used for each of the channel grab samples.

1. The entire sample (gravel, sand and fines) is weighed and then split into a gravel and sand portion for further analysis.
2. The gravel portion of the sample is washed to remove any adhering sand, silt or clay and is then dried and weighed. The fines from the wash were retained and passed (wet sieved) through a 230 mesh sieve to extract any sand sized material. The sand caught in this manner was added to the rest of the sand from the sample and the remainder of the wash material was discarded.
3. The sand fraction of the sample is wet sieved through the 230 mesh sieve to remove all silt and clay sized material. The sand is then dried and weighed. Again the silt and clay in the wash bucket were discarded.
4. The percentage of the total sample weight which was due to the silt and clay sized detritus is determined by summing the weights of the clean sand and gravel from steps 2 and 3 and subtracting from the total sample weight of step 1.
5. The gravel portion of the sample is separated into seventeen size classes by hand sieving, the sediment obtained for each class being separately weighed and retained. The grain size data is presented in appendix C.
6. The sand portion of the sample is broken down to an approximately 115 gm representative sample, the split factor obtained and then separated into ten size classes

using a Ro-Tap sediment shaker. The sediment of each class is separately weighed and retained. This data is also presented in appendix C.

The grain size data obtained in the above manner was used with an A.P.L. interactive computer plotting package known as 8 plot to construct the cumulative grain size curves for each of the channel samples. These curves are presented and discussed in the next chapter.

4. The Active Channels Of Beauty Creek Flats

4.1 Morphologic And Hydraulic Characteristics Of The Active Channels

The first objective of the investigation as stated in section 1.2, p. 6 is addressed in this section. Rather than discuss the variation in each channel parameter over the valley train a statistical summary table (table 4-1, p. 56) is presented which is derived from tables A-1 and A-2 of appendix A. This table provides the maximum, minimum, mean and standard deviation of each parameter for Beauty Creek Flats as a whole, and the mean and standard deviation of each parameter for each of the three reaches. Seven morphologic and seven hydraulic parameters are described in table 4-1. The statistics on bed material grain size (D_{50} and D_{90}), sediment ratios, roughness, average bottom shear stress, slope and channel length were determined using only channel data from the theoretical discharge data set. The statistics on the remainder of the parameters contained in the table were determined by combining the two data sets. It should be noted that in so doing the statistics on parameters such as width for example, are determined by combining channel average values of the theoretical discharge data set (two or three flow cross sections per channel) with values of the measured discharge data set (only one flow cross section per channel). It is estimated that approximately 70% of the qualifying active channels were investigated from each of the three reaches and that therefore, approximately 70% of the qualifying active channels on Beauty Creek Flats during the period of August 4-15, 1977 are represented by table 4-1.

Table 4-1 shows that the mean value of the parameters progressively decreases in value from the upper to the lower reach of Beauty Creek Flats with the exception of Froude number, width to depth ratio, depth, width and area. Of these, width to depth ratio progressively increases down Beauty Creek Flats while the remainder show no consistent down valley behaviour. Seven features of the data warrant discussion.

1. Although the average water surface slopes of the three reaches are equal to the corresponding average bed slopes, reference to table A-2 demonstrates that in the majority of channels of this data set the former was slightly greater than the latter.
2. A dominant control by slope (which is itself determined by the alluvial fan at the bottom of Beauty Creek Flats) is manifest in the fact that velocity decreases down the study area even though roughness (Mannings n) is also decreasing. An approximate order of magnitude difference exists between the S_w of the upper and middle reaches and the S_w of the lower reach due to the latter's proximity to the alluvial fan.
3. The mean values for discharge (Q) represent the average discharge per channel in each of the three reaches. As

Table 4-1. Statistical summary table of the active channels investigated on Beauty Creek Flats.

					Beauty Creek Flats				
parameter	reach	$\bar{X}$	std. dev.	N	max.	min.	$\bar{X}$	std. dev.	N
flow area (m^2)	upper	2.64	2.72	20	9.86	0.19	2.39	2.49	60
	middle	1.92	1.97	20					
	lower	2.60	2.78	20					
length (m)	upper	157.83	56.57	10	252.37	26.52	100.89	67.88	30
	middle	103.27	60.49	10					
	lower	41.58	21.68	10					
S_w	upper	0.011	0.001	10	0.016	0.002	0.008	0.004	29
	middle	0.010	0.003	10					
	lower	0.004	0.001	9					
S_b	upper	0.011	0.004	10	0.015	+ 0.010	0.008	0.005	30
	middle	0.010	0.003	10					
	lower	0.004	0.004	10					
av. width (m)	upper	8.10	5.29	20	24.38	1.68	8.05	5.00	60
	middle	7.63	5.02	20					
	lower	8.41	4.89	20					

Table 4-1. (continued)

					Beauty Creek Flats				
parameter	reach	$\bar{X}$	std. dev.	N	max.	min.	$\bar{X}$	std. dev.	N
av. depth (m)	upper	0.26	0.10	20	0.49	0.10	0.23	0.10	60
	middle	0.21	0.07	20					
	lower	0.22	0.11	20					
av. w:d	upper	30.76	10.87	20	67.37	13.63	35.21	13.05	60
	middle	36.63	15.59	20					
	lower	38.24	11.61	20					
$\bar{V}_s$ (m/s)	upper	1.48	0.46	20	2.44	0.58	1.25	0.43	60
	middle	1.28	0.36	20					
	lower	0.99	0.31	20					
$\bar{\tau}_o$ (kg/m^2)	upper	31.69	11.40	10	48.06	5.44	20.62	12.47	30
	middle	18.67	4.67	10					
	lower	11.50	10.79	10					
Fr	upper	0.72	0.15	20	1.05	0.29	0.66	0.17	60
	middle	0.72	0.16	20					
	lower	0.54	0.12	20					

Table 4-1. (continued)

					Beauty Creek Flats				
parameter	reach	$\bar{X}$	std. dev.	N	max.	min.	$\bar{X}$	std. dev.	N
Re_{ch}	upper	220810	142715	20	513333	36667	174005	120245	60
	middle	165577	105476	20					
	lower	135628	97338	20					
n	upper	0.055	0.009	10	0.084	0.033	0.051	0.013	30
	middle	0.050	0.014	10					
	lower	0.047	0.015	10					
D_{50} (mm)	upper	45.16	14.74	10	69.55	8.28	30.21	16.63	30
	middle	31.73	10.36	10					
	lower	13.74	3.75	10					
D_{90} (mm)	upper	99.60	10.76	10	116.15	18.64	68.34	32.28	30
	middle	71.08	26.43	10					
	lower	34.34	12.85	10					
gravel to sand ratio	upper	30.75	30.49	10	111.98	3.24	19.06	23.58	30
	middle	20.54	22.57	10					
	lower	5.90	2.51	10					
Q (m^3/s)	upper	3.27	4.17	20	14.59	0.08	2.47	3.20	60
	middle	2.14	2.72	20					
	lower	2.02	2.45	20					

mentioned above these decrease downstream. This occurs despite an increase in the total discharge in the middle and lower reaches due to the discharge additions from the unnamed creek and Beauty Creek, respectively. Although the number of active channels in each reach was never tallied this is indirect proof of a progressive increase in the number of active channels down Beauty Creek Flats.

4. A strong progressive decrease in grain size is noted for both the D_{50} and D_{90} percentiles. In both cases the average in the lower reach is only approximately one third of the average in the upper reach. On average $D_{90} = 2.30 D_{50}$. Grain size must be considered a major factor in the variation of channel behaviour among the three reaches of Beauty Creek Flats.

5. The mean widths indicate that there is a decrease in the middle reach and an increase (to a maximum) in the lower reach. Initially, the figure for the lower reach may seem a bit confusing since the average discharge per channel indicates that there is an increase in the number of channels in this reach which would cause one to expect a decrease in average width as was the case in the middle reach. A consideration of the magnitude of the increase in the number of channels between the upper and middle and middle and lower reaches plus a consideration of the size of the total discharge increase in the middle (due to the unnamed creek) and

lower reach (due to Beauty Creek) explains this. Using the average discharge per channel as an index, representing the increase in the number of channels, there is an approximately 35% increase in the number of active channels in the middle reach and only an approximate 6% increase in the lower reach. In conjunction with this, although the two tributaries were not gauged it was obvious that the discharge contribution from Beauty Creek exceeded that from the unnamed creek. The combined effect of a smaller increase in the number of channels and a larger increase in the total discharge resulted in the lower reach channels being wider on the average. Also, the reduced slope in the lower reach would contribute to this increased width.

In the above context it is reasonable to infer that the lower reach channels, on average, should experience overbank flows more frequently than the channels of the middle or upper reach. Since this would supply more fine interstitial sediment to the inactive areas of the lower reach it is suggested that this may account for an upstream progression of the grassy area located at the bottom end of this reach (see figure 1-3). The upstream growth of this area was noted upon examination of air photos taken in different years.

6. During data acquisition the bankfull discharges were capable of moving only the smaller gravel sizes of the

channels. The coarser material was moved for a short distance only when it was dropped into the flow from adjacent banks via winnowing of interstitial fines.

It is instructive to compare these observations of sediment transport to the predictions provided by Baker and Ritter's (1975) critical shear stress diagram. This diagram is applicable to coarse bedload material and was constructed by standardizing the method of critical shear stress calculation for six sets of field competence data. In so doing they hoped to remove much of the scatter normally encountered in such plots where data derived by different techniques are grouped together. The correlation coefficient obtained for their regression was 0.92 indicating a high degree of success (see their figure 1, p. 976). Their scour diagram is presented below as figure 4-1. The average bottom shear stress values of the upper, middle and lower reach are plotted against the average D_{90} value of each reach (see table 4-1 for this data). The plotting position of the three reaches is to the right of the critical shear stress line by a significant distance. This indicates that the D_{90} of the channels in all three reaches should have been in transport. The critical shear stress for the average D_{90} of the upper, middle and lower reach channels as predicted by Baker and Ritter's diagram is approximately 2.20, 1.20 and 0.30 kg/m^2, respectively. This is much less than the calculated average bottom shear stress for each reach. Assuming the observations on coarse gravel transport are accurate (at times these were difficult due to the amount of rock flour and coarser fines being transported in suspension) the data of this study indicate that the critical shear stress values as predicted from Baker and Ritter's diagram are too low. Although the imbricated, underloose state of the channel bed gravel may be held partially accountable for this discrepancy the fact that the data used in the construction of the diagram included channels which also would have been underloose (Fahnestock's (1963) channel data) and the very large differential between the predicted critical shear stress values and the calculated average bottom shear stress values indicates that the diagram may be inaccurate for armoured, shallow and fast gravel bed channels.

The within reach variation in bed material grain size is represented in figures 4-2, 4-3 and 4-4, p. 65 - 67 which present the cumulative curves of the bed material for the channels of the theoretical discharge data set grouped into the three reaches of Beauty Creek Flats. It was mentioned in chapter three that the method of obtaining the samples (shovel and bucket) forces a bias in the resulting grain size distribution in favour of the coarse portion of the sample. The strong positive skewness indicated by the curves in figures 4-2, 4-3 and 4-4 reflect this sampling bias. This was unavoidable since the more sophisticated equipment for

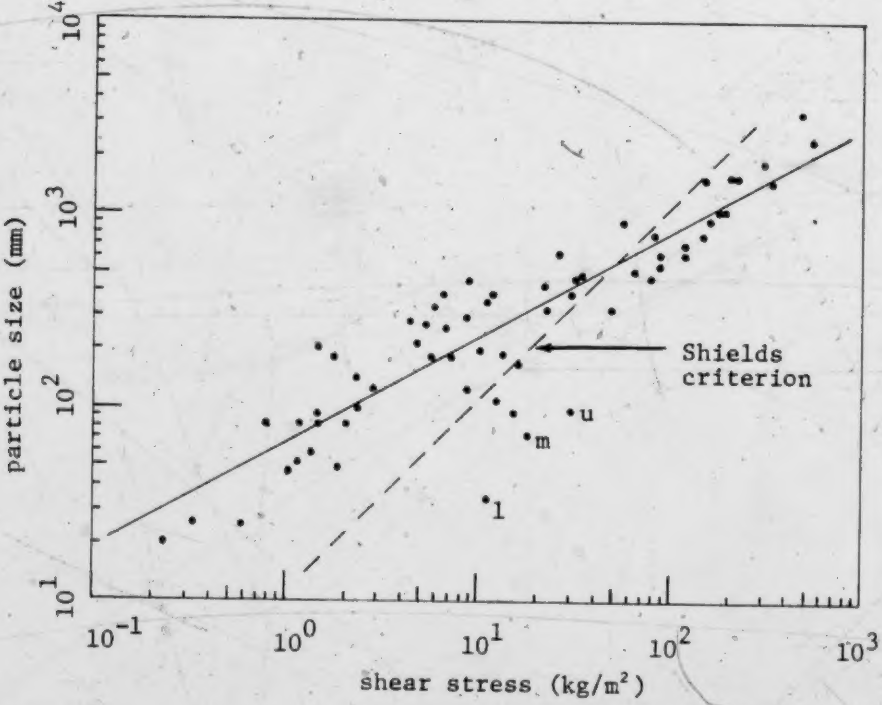


Figure 4-1. Baker and Ritter's (1975, fig. 1) plot of particle size against mean shear stress for coarse bedload material transported in rivers, canals and flood channels. In their figure the data points were differentiated into six source papers. The plotting position for the average D_{90} of the upper, middle and lower reach against the average bottom shear stress of each reach is indicated by u, m and l.

sampling bed material load which may have avoided this problem were unavailable. There are several procedures available for correcting sample bias arising from sampling technique (Kellerhals and Bray, 1971 and Potter, 1979), however these procedures are appropriate only when the surface of the channel bed is similar to the underlying sediment, or in other words when channel armouring does not exist (Potter, 1979, p. 22). However, since the samples are dominantly gravel (see table 4-1) the weight of the fines lost by the sampling method would have only been a small percentage of the total weight. For this reason the D_{50} and D_{90} values obtained from the cumulative curves are considered to be in excess of the true values by only a small amount. The D_{50} and D_{90} values for the channels of the theoretical discharge data set are included in table A-2 of appendix A. It can be seen from figures 4-2 to 4-4 that considerable overlap exists for the curves of the upper and middle reach whereas the curves of the lower reach are easily distinguished from these curves by their finer grain sizes.

Appendix B contains the flow cross sections obtained for the channels of the theoretical discharge data set. A within reach and in some instances a within channel significant variation in flow cross section shape is indicated in these diagrams. The large width to depth ratios characteristic of channels in coarse, noncohesive alluvium is apparent in these cross sections. In many instances a composite nature is revealed such as in the case of the top and bottom flow cross sections of channel 1 of transect 4 (4/1/T and 4/1/B). For such channels it is apparent from the drastic decrease in depth that a smaller parent channel has been enlarged by the scouring associated with overtopping of the banks.

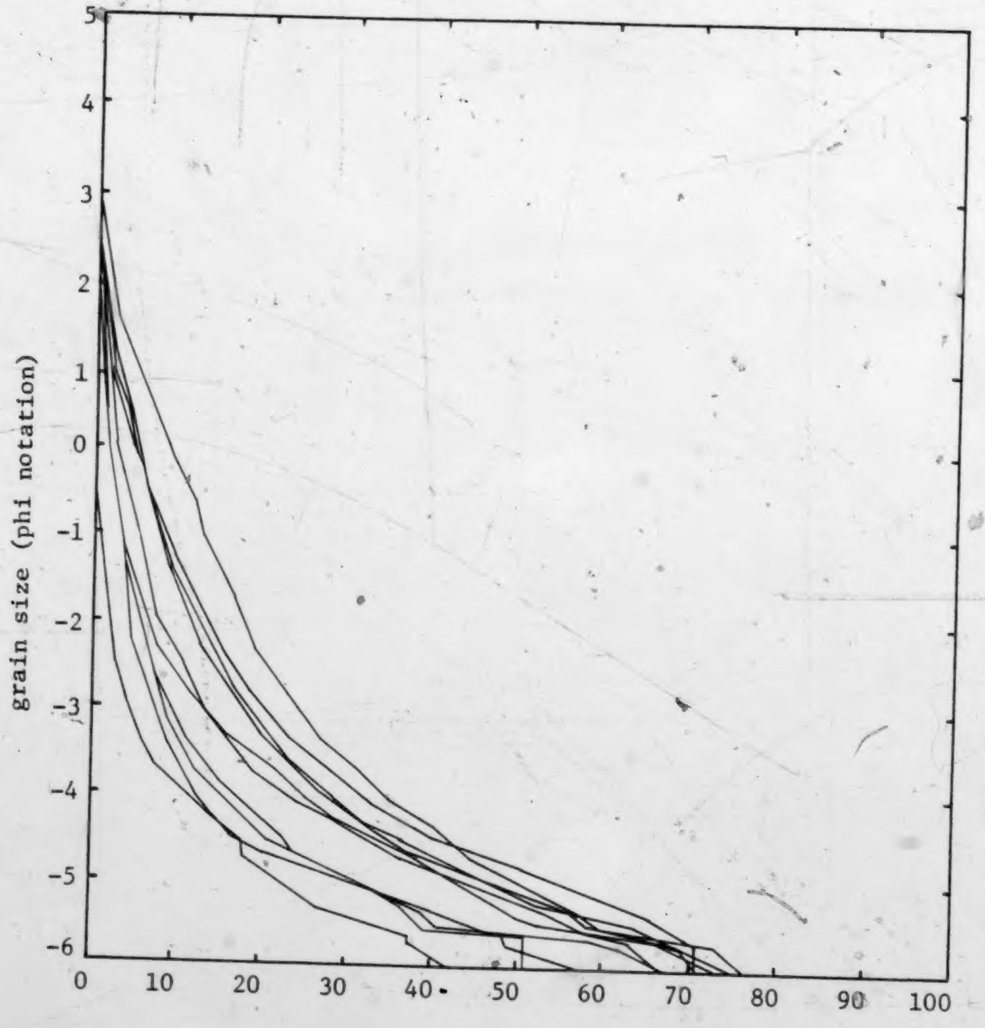


Figure 4-2. Cumulative curves of the grab samples from the upper reach channels of the theoretical discharge data set.

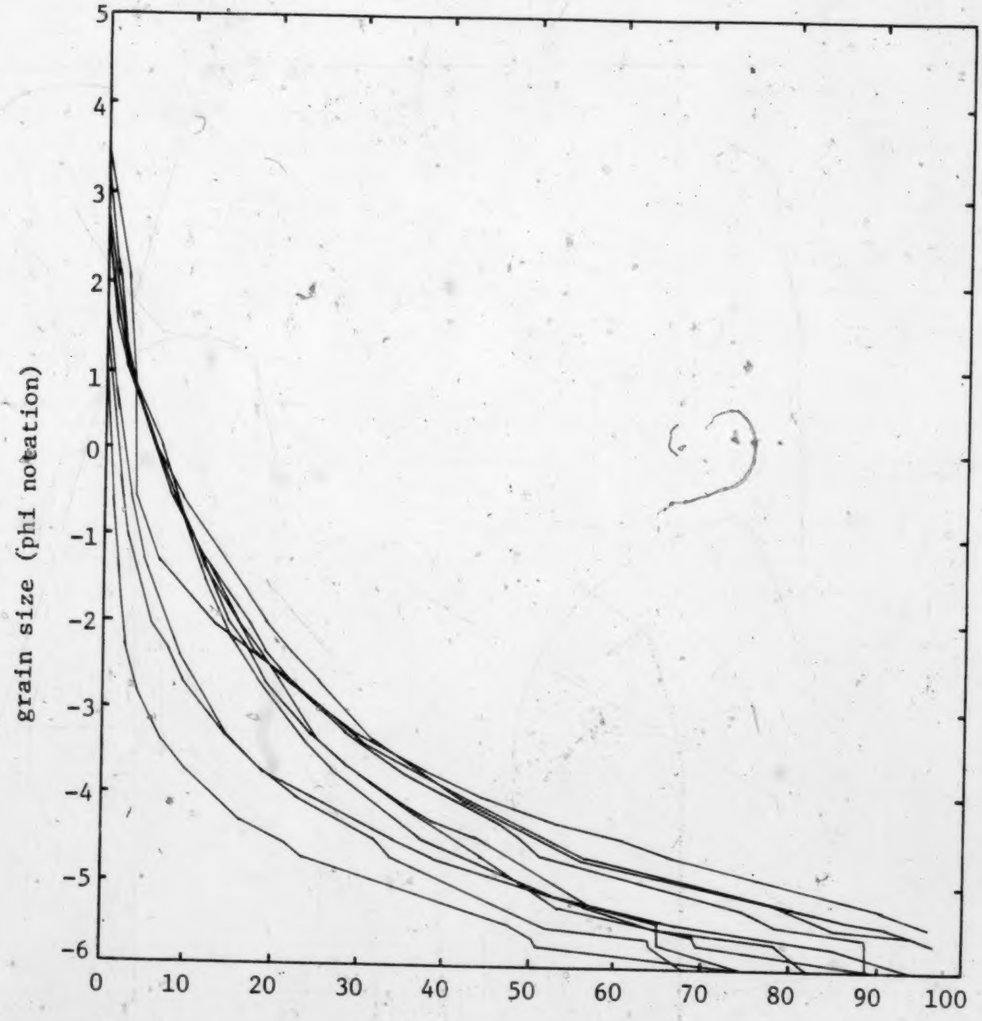


Figure 4-3. Cumulative curves of the grab samples from the middle reach channels of the theoretical discharge data set.

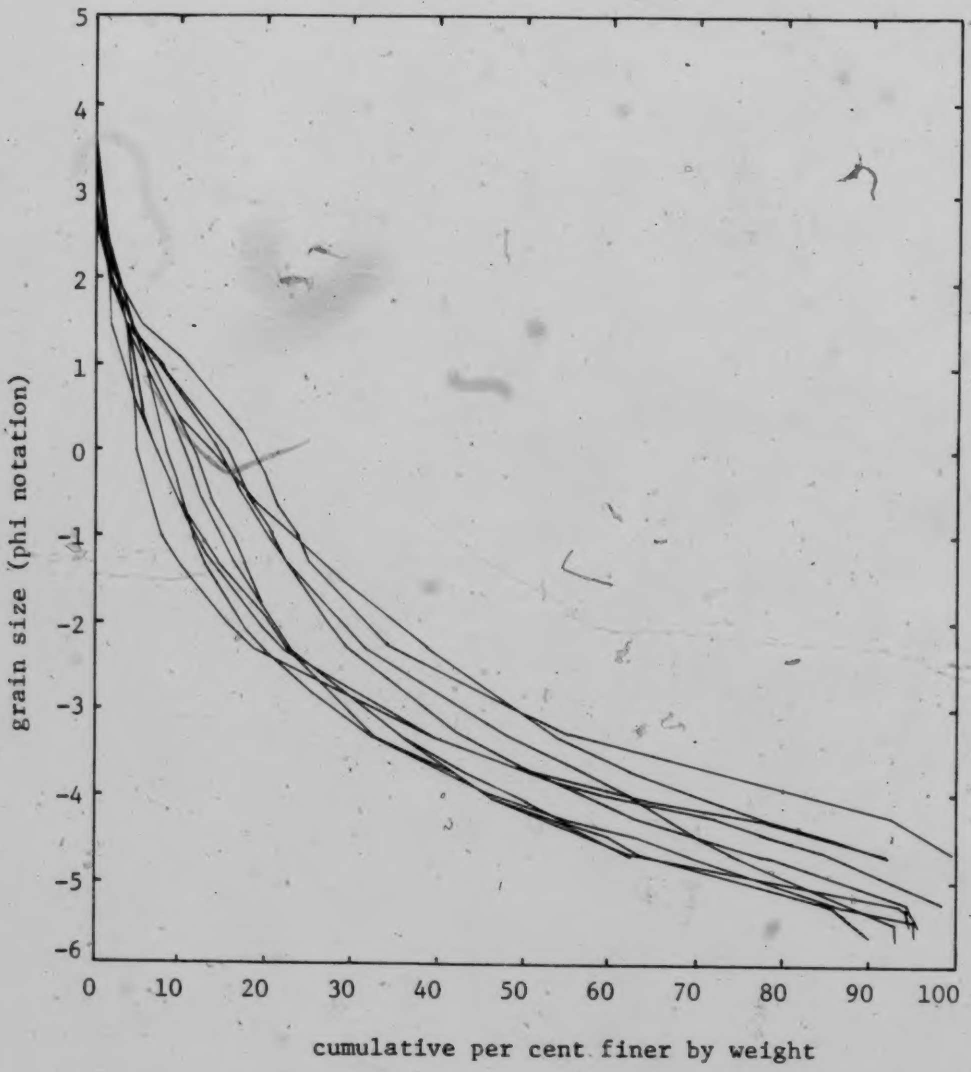


Figure 4-4. Cumulative curves of the grab samples from the lower reach channels of the theoretical discharge data set.

4.2 The Hydraulic Geometry Of The Active Channels

4.2.1 General

The second objective of this investigation, as stated in section 1.2, was the interpretation of a variation in channel behaviour through the development of hydraulic geometry equations. That objective is discussed in this section (4.2). Power functions are presented (in 4.2.2) which indicate that there is a variation in channel behaviour among the three reaches of Beauty Creek Flats. An interpretation of the reason for this variation is suggested (in 4.2.3) with the emphasis on the explanation of the variation in the exponents of the hydraulic geometry equations. The need for such an approach was emphasized by Park (1977, p. 144) when he stated that "...in most published studies of hydraulic geometry there is little attempt to account for variations in hydraulic geometry relationships..." and "it is clear that perhaps the greatest problem remains that of accounting for observed variations in the hydraulic geometry relationships". An explanation of the variation in the coefficients of the hydraulic geometry relations is not attempted. Coefficients reflect local variations in sediment and flow characteristics. Although their interpretation would help explain the variation in channel behaviour downstream, the detailed information that is required for their interpretation was not obtained.

The hydraulic geometry relationships presented in section 4.2.2 were derived by collating tables A-1 and A-2, and then breaking the composite data set down into three groups of data, one for the upper, middle and lower reach of Beauty Creek Flats. In this manner, the variation in channel behaviour downstream could be examined. As explained in section 3.3 the channels were chosen at random (measured discharge data set) and by running transects across the valley train at various locations along Beauty Creek Flats (theoretical discharge data set). Channels in such a fluvial environment (braided gravelly outwash) are characterized by the regular occurrence of riffles and pools along the flow path. The former are shallower, higher velocity areas found at the beginning of two channels at a bifurcation point. In contrast, pools are areas of increased depth and decreased velocity found at the confluence of two channels. As would be expected these two areas differ significantly in their hydraulic characteristics. Richards (1976) has found that the rate of increase of depth and velocity for a riffle area is greater and less than, respectively, corresponding rates of increase for a pool. Church (1972, table 31, p. 191) determined the hydraulic geometry exponents of width, depth, velocity and area for riffles and pools of Baffin Island sandar. Also, Knighton (1975) has found that riffles and pools may be distinguished by differences in the response of flow resistance, slope and width to an increase in discharge. For these reasons, when a channel was intersected on a transect the flow cross sections were not located in either of these two areas. Although it was realized that the differences between riffles and pools are minimized at bankfull discharge (Leopold and Langbein, 1962), it was felt that such remaining variation might at least partially mask a downstream variation in channel response.

Since the emphasis of this investigation is the explanation of the downstream hydraulic geometry the principle of constant frequency of discharge becomes of paramount importance. This principle was explained in section 1.1. Ideally, in a single channel river situation this principle would be adhered to by examining the discharge records of each station along the river and simply picking those discharges (and accompanying cross sectional data) from each station's records that have the same frequency of occurrence. Any variation in the hydraulic geometry relations between stations would then be representing real differences and not just differences arising from comparing channel response at different discharges. For a braided river, adherence to this principle is much more difficult since it is not practical to place a gauging station on each anabranch. On Beauty Creek Flats, by grouping the data into three reaches and developing hydraulic geometry relations for each reach, the reach becomes in effect a station. It is important therefore, to be able to demonstrate that for each reach the average discharge of the period of data acquisition was approximately constant. Also, since it was impossible to refer to gauging station records, the concern had to be for a similarity in average discharge magnitude rather than a similarity in frequency of occurrence. As has been stated, the adopted dominant discharge during the period of data acquisition for all three reaches was from slightly below to, in some instances, slightly above bankfull discharge. Discharge varied due to both diurnal fluctuations in stage and weather induced differences in maximum discharge from one day to another. An indication of the degree of similarity in average discharge for the period of data acquisition for each reach may be gained by reference to the stage recorder chart from the gauging station at the beginning of Beauty Creek Flats (see figure 1-3). To do so, one must assume that a variation in stage at this station would be matched by similar variations in stage on the two tributaries. This is felt to be a reasonable assumption since all three locations have a weather controlled discharge. In this context then, the variation in stage at the gauging station may be considered to be representative of the variations in stage on Beauty Creek Flats as a whole. The technique used to determine the average stage (which is representative of discharge) for each reach's data acquisition period was to firstly determine on which days of the period August 4-15, the data on the channels of each reach was obtained. Once this was done the average stage for each day of the August 4-15 interval was determined by averaging the minimum and maximum stage of each day as determined from the stage recorder chart of the gauging station. To obtain the average stage for a reach's period of data acquisition it was necessary to weight the daily average stages according to the number of channels investigated on that particular day. In this fashion a weighted average stage was obtained for each day of a given reach's period of data acquisition. The weighted average stage for the reach was then obtained simply by averaging the daily weighted average stages of that reach's data gathering period. Table 4-2 gives each step of the procedure for each reach. The resulting weighted reach averages are 0.16, 0.11 and 0.15 m for the upper, middle and lower reaches respectively. The similarity of these figures is considered to be sufficient to indicate that the variation in channel behaviour between the three reaches of Beauty Creek Flats as indicated by the hydraulic geometry exponents to be presented subsequently, represents actual reach differences rather than differences attributable to the time at which the data for each reach was gathered.

UPPER REACH					
date	av. stage (m)	channels/date	weight factor	wt. av. stage (m)	wt. reach average (m)
Aug. 4	0.54	5	0.25	0.14	0.16
5	0.48	5	0.25	0.12	
12	0.72	4	0.20	0.14	
13	0.72	6	0.30	0.22	

MIDDLE REACH					
date	av. stage (m)	channels/date	weight factor	wt. av. stage (m)	wt. reach average (m)
Aug. 6	0.45	2	0.10	0.05	0.11
7	0.47	6	0.30	0.14	
8	0.55	2	0.10	0.06	
13	0.72	2	0.10	0.07	
14	0.60	8	0.40	0.24	

LOWER REACH					
date	av. stage (m)	channels/date	weight factor	wt. av. stage (m)	wt. reach average (m)
Aug. 9	0.66	4	0.20	0.13	0.15
10	0.57	6	0.30	0.17	
14	0.60	4	0.20	0.12	
15	0.52	6	0.30	0.16	

Table 4-2. The procedure used to estimate the degree of similarity in flow magnitude between the data gathering periods of the upper, middle and lower reach of Beauty Creek Flats.

4.2.2 Presentation Of The Hydraulic Geometry Relations

In this section the power functions developed for the upper, middle and lower reaches of Beauty Creek Flats are presented. Four channel characteristics are regressed against discharge for each reach. The comparison of the exponent of the power function for a given parameter, for example width, to corresponding exponents in the other two reaches is an indication of the magnitude of the variation in channel response between the three reaches with respect to this particular channel characteristic. By combining this with similar comparisons done for the other channel characteristics the amount of variation in channel behaviour down Beauty Creek Flats is indicated.

It is important to distinguish between the average value of a particular parameter for a reach as is given in table 4-1 and the rate of change of that parameter with an increase in discharge which is indicated by the exponent of the power function. A given parameter may increase or decrease with an increasing discharge (positive or negative correlation respectively). A set of channels or a reach (in the case of the average values given in table 4-1) may be shallower than another but may have a greater rate of depth increase with increasing discharge. In this case, the shallower reach may have the smallest average depth but the largest positive exponent for its power function.

Ideally, when hydraulic geometry relations are developed for a station the stream data from which they are derived has been obtained by repetitive flow measurements over a period of time at exactly the same flow cross section. For the three reaches of Beauty Creek Flats only one set of measurements was obtained per channel. Twenty channels were investigated in each reach and combined to constitute the data set from which the hydraulic geometry relations for that reach were derived. This approach in effect, constitutes taking stream measurements at various flow cross sections in the vicinity of a designated station. This is not an invalid approach but the amount of scatter would be expected to be significantly greater than if the data came from the same flow cross section (Wolman, 1955, in Fahnestock, 1963, p. 13).

As mentioned above, power functions were determined for four channel characteristics for each reach. The four characteristics were width, average depth, average surface velocity and water surface slope. In all cases the independent variable was discharge. Power functions for the same four parameters were also developed for Beauty Creek Flats as a whole by combining the data sets of the three reaches.

A standard notation exists for the coefficients and exponents of the power functions for the four channel characteristics to be presented. The general form of the relation for each of these parameters is as follows:

$$W = aQ^b$$

$$d = cQ^f$$

$$V = kQ^m$$

$$S = tQ^z$$

In the subsequent interpretation (section 4.2.3) the exponents for a particular relationship may be referred to by their corresponding letter.

The power function relationships were derived from base 10 log-log plots of the data on each reach. The use of logarithms is convenient primarily due to the fact that river discharge tends to be log-normally distributed (Blatt, Middleton and Murray, 1972, table 3-2, p. 39). Histograms of both transformed and untransformed data were examined. The logarithmic transformation produced a significantly more normal distribution for the discharge and width data while only minor improvement was noted in the distributions of the other parameters. The normalizing effect of the transformation makes the data more amenable to various statistical tests which require an assumption of normality.

The power functions determined for each reach and for Beauty Creek Flats as a whole are presented below followed by the corresponding graphs as figure 4-5 A, B, C and D. It will be noted that although twenty channels were investigated in each reach the water surface slope relations were determined with only ten data points (only nine for the slope relation in the lower reach). This results from acquiring slope measurements for the theoretical discharge data set only (see section 3.3). It should also be noted that the average depth-discharge relation was determined by regressing the average depth values of tables A-1 and A-2 against discharge rather than the corrected depth values which were used in the theoretical determination of discharge.

upper reach channels

$W = 5.69\ Q^{0.39}$ $r^2 = 0.86$ $N = 20$ Eq. 4.1

$\bar{d} = 0.21\ Q^{0.28}$ $r^2 = 0.83$ $N = 20$ Eq. 4.2

$\bar{V}_s = 1.25\ Q^{0.23}$ $r^2 = 0.68$ $N = 20$ Eq. 4.3

$S_w = 0.01\ Q^{0.01}$ $r^2 = 0.02$ $N = 10$ Eq. 4.4

middle reach channels

$W = 6.00\ Q^{0.47}$ $r^2 = 0.82$ $N = 20$ Eq. 4.5

$\bar{d} = 0.19\ Q^{0.25}$ $r^2 = 0.83$ $N = 20$ Eq. 4.6

$\bar{V}_s = 1.19\ Q^{0.20}$ $r^2 = 0.57$ $N = 20$ Eq. 4.7

$S_w = 0.01\ Q^{-0.10}$ $r^2 = 0.16$ $N = 10$ Eq. 4.8

lower reach channels

$W = 7.05\ Q^{0.45}$ $r^2 = 0.85$ $N = 20$ Eq. 4.9

$\bar{d} = 0.20\ Q^{0.36}$ $r^2 = 0.90$ $N = 20$ Eq. 4.10

$\bar{V}_s = 0.94\ Q^{0.15}$ $r^2 = 0.38$ $N = 20$ Eq. 4.11

$S_w = 0.004\ Q^{-0.28}$ $r^2 = 0.57$ $N = 9$ Eq. 4.12

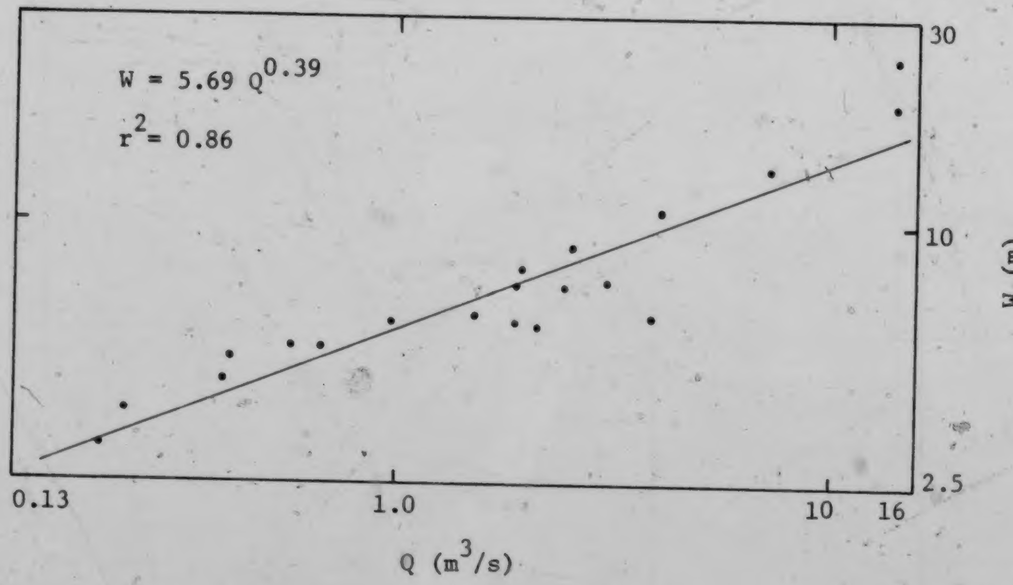
Beauty Creek Flats

$W = 6.21\ Q^{0.42}$ $r^2 = 0.81$ $N = 60$ Eq. 4.13

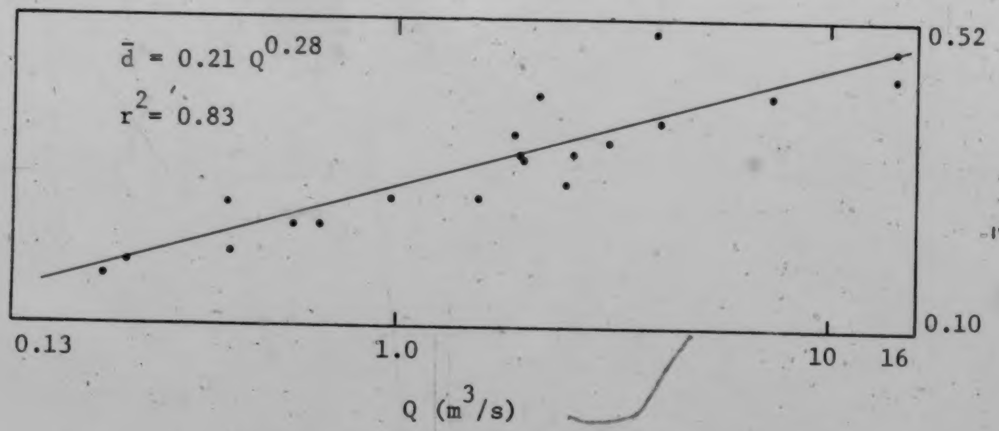
$\bar{d} = 0.20\ Q^{0.30}$ $r^2 = 0.84$ $N = 60$ Eq. 4.14

$\bar{V}_s = 1.12\ Q^{0.21}$ $r^2 = 0.51$ $N = 60$ Eq. 4.15

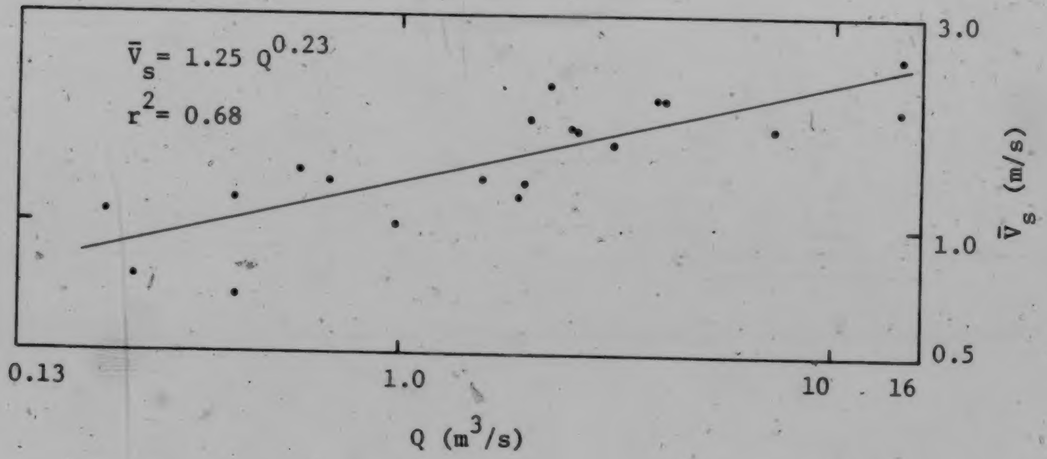
$S_w = 0.01\ Q^{-0.01}$ $r^2 = 0.0003$ $N = 29$ Eq. 4.16



W = 5.69 Q^0.39
r^2 = 0.86
30
10
2.5
W (m)
0.13
1.0
10
16
Q (m^3/s)



d̄ = 0.21 Q^0.28
r^2 = 0.83
0.52
0.10
d̄ (m)
0.13
1.0
10
16
Q (m^3/s)



V̄s = 1.25 Q^0.23
r^2 = 0.68
3.0
1.0
0.5
V̄s (m/s)
0.13
1.0
10
16
Q (m^3/s)

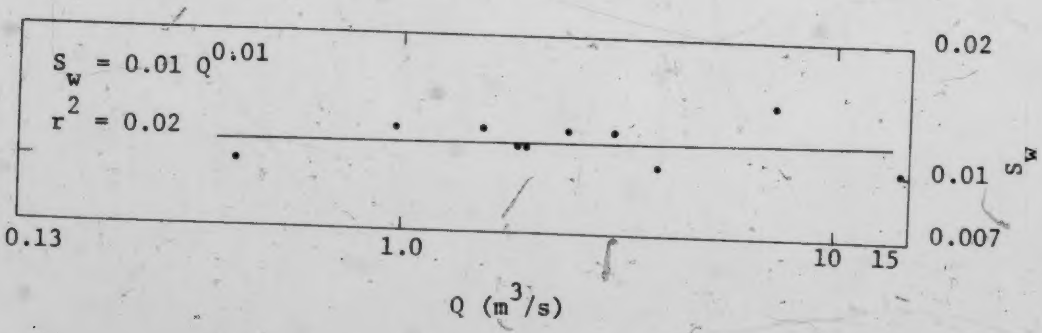
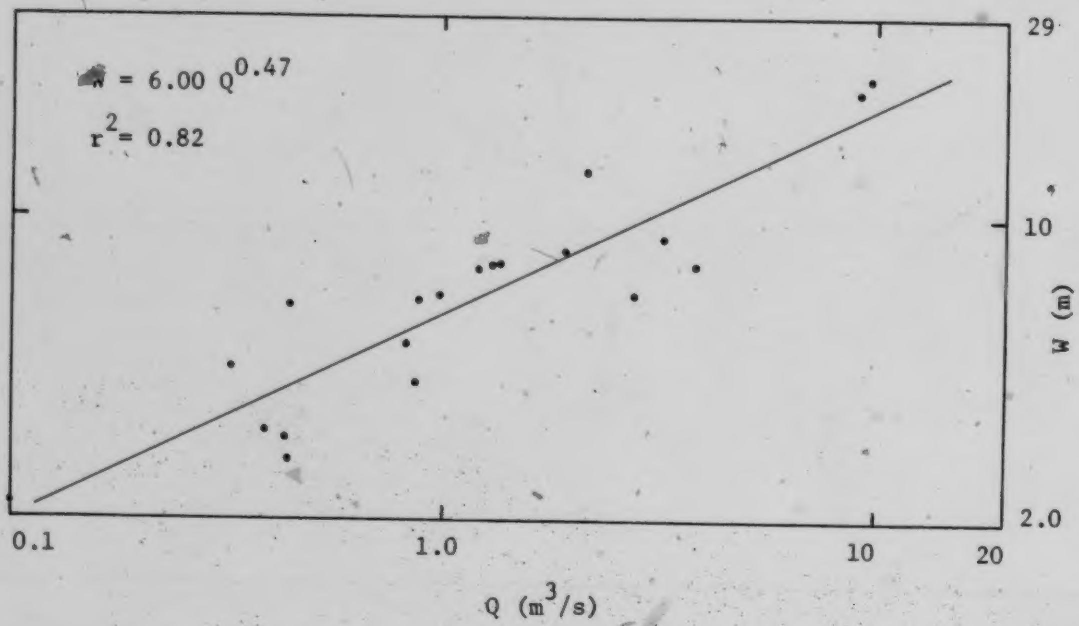
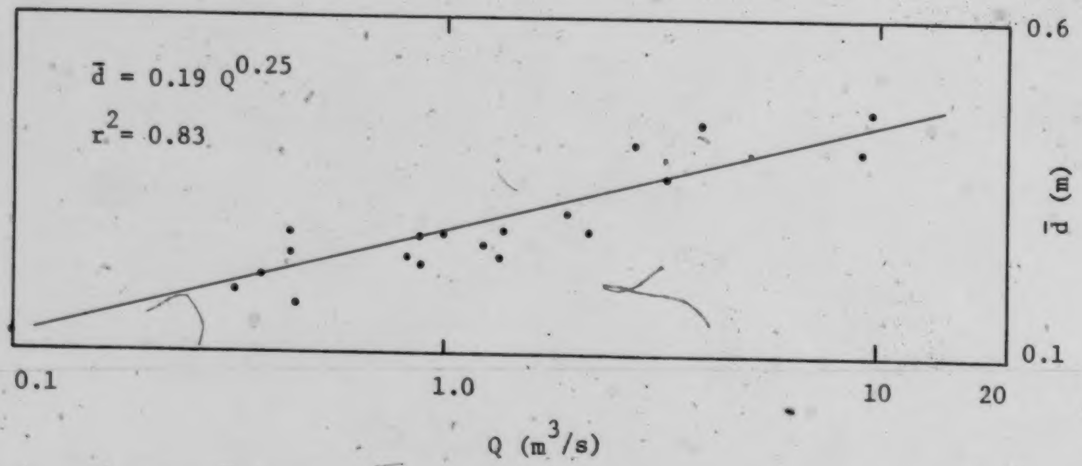
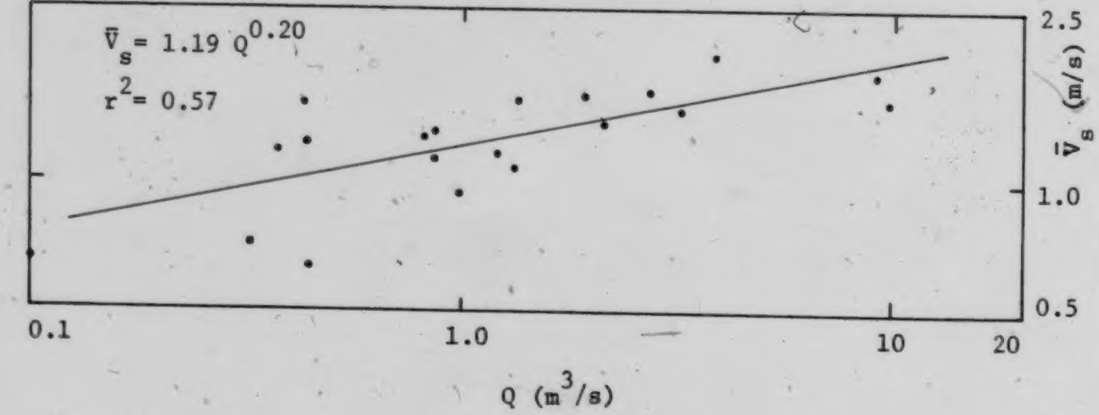


Figure 4-5 A. Log-log plots (4) of the hydraulic geometry relations developed for the upper reach of Beauty Creek Flats; the previous page is included in this figure.


w = 6.00 $Q^{0.47}$
r^2= 0.82
29
10
2.0
w (m)
0.1
1.0
10
20
Q (m^3/s)


$\bar{d}$ = 0.19 $Q^{0.25}$
r^2= 0.83
0.6
0.1
$\bar{d}$ (m)
0.1
1.0
10
20
Q (m^3/s)


$\bar{V}_s$= 1.19 $Q^{0.20}$
r^2= 0.57
2.5
1.0
0.5
$\bar{V}_s$ (m/s)
0.1
1.0
10
20
Q (m^3/s)

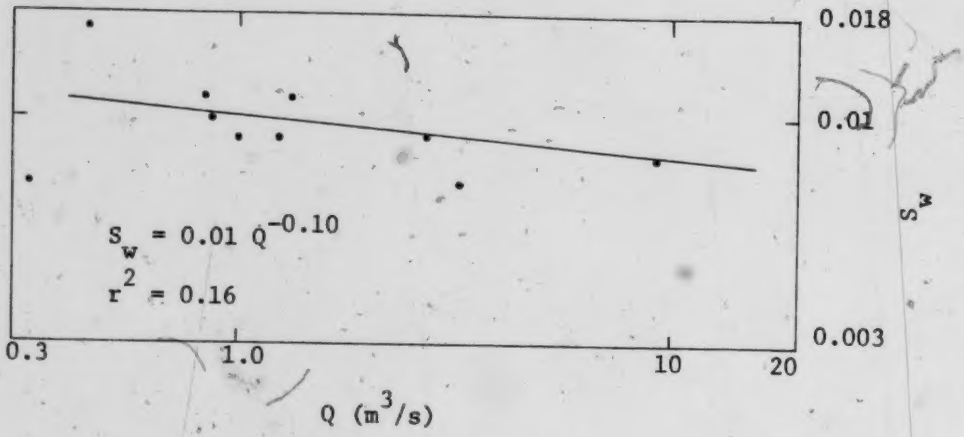
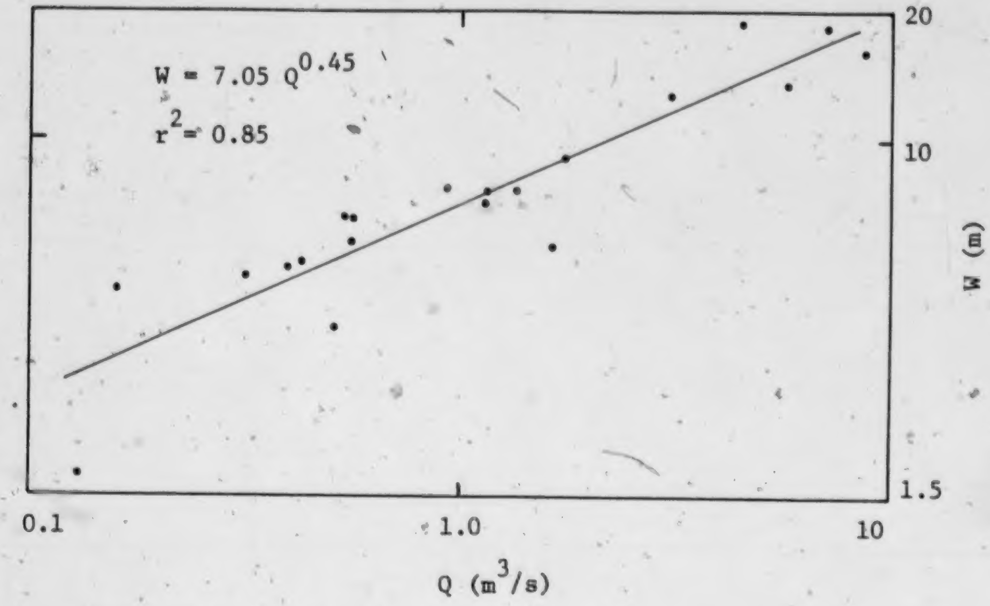
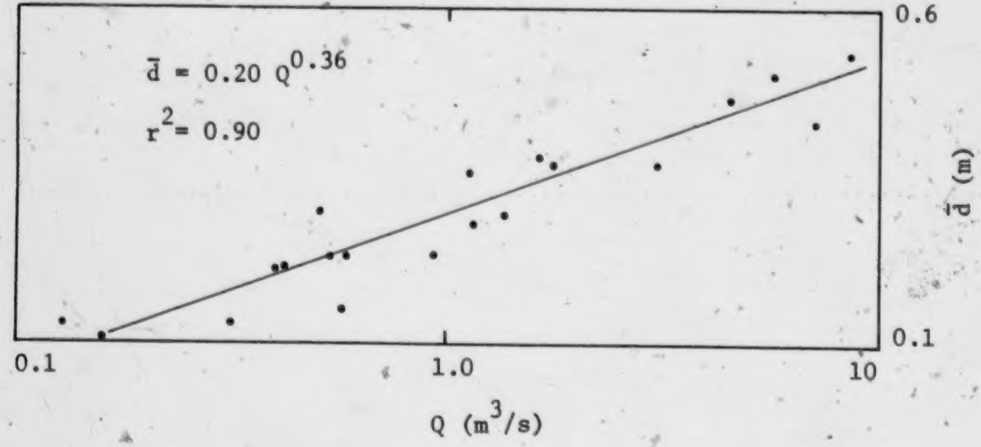
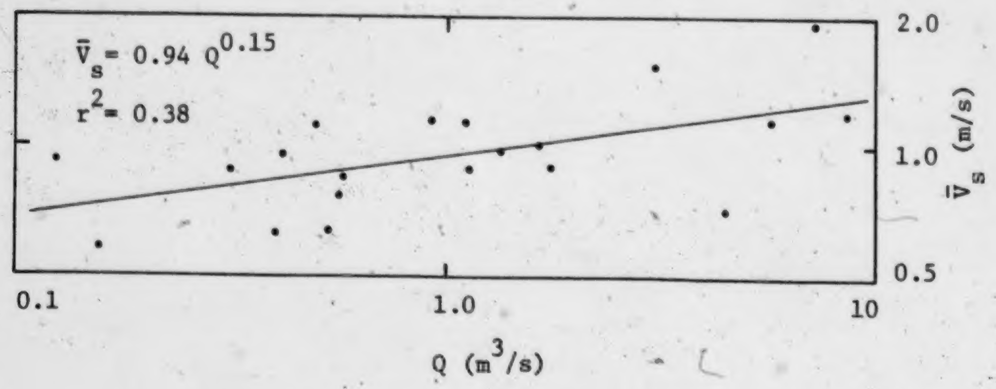


Figure 4-5 B. Log-log plots (4) of the hydraulic geometry relations developed for the middle reach of Beauty Creek Flats; the previous page is included in this figure.


$W = 7.05\ Q^{0.45}$
$r^2 = 0.85$
20
10
1.5
W (m)
0.1
1.0
10
Q (m^3/s)


$\bar{d} = 0.20\ Q^{0.36}$
$r^2 = 0.90$
0.6
0.1
$\bar{d}$ (m)
0.1
1.0
10
Q (m^3/s)


$\bar{V}_s = 0.94\ Q^{0.15}$
$r^2 = 0.38$
2.0
1.0
0.5
$\bar{V}_s$ (m/s)
0.1
1.0
10
Q (m^3/s)

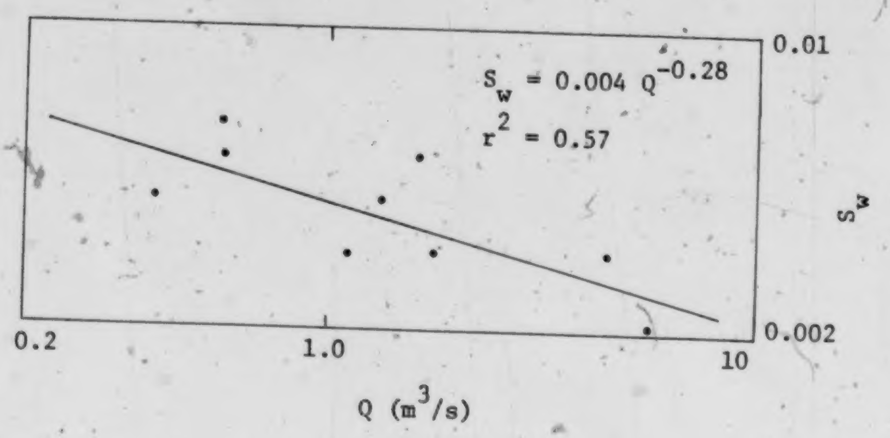


Figure 4-5 C. Log-log plots (4) of the hydraulic geometry relations developed for the lower reach of Beauty Creek Flats; the previous page is included in this figure.

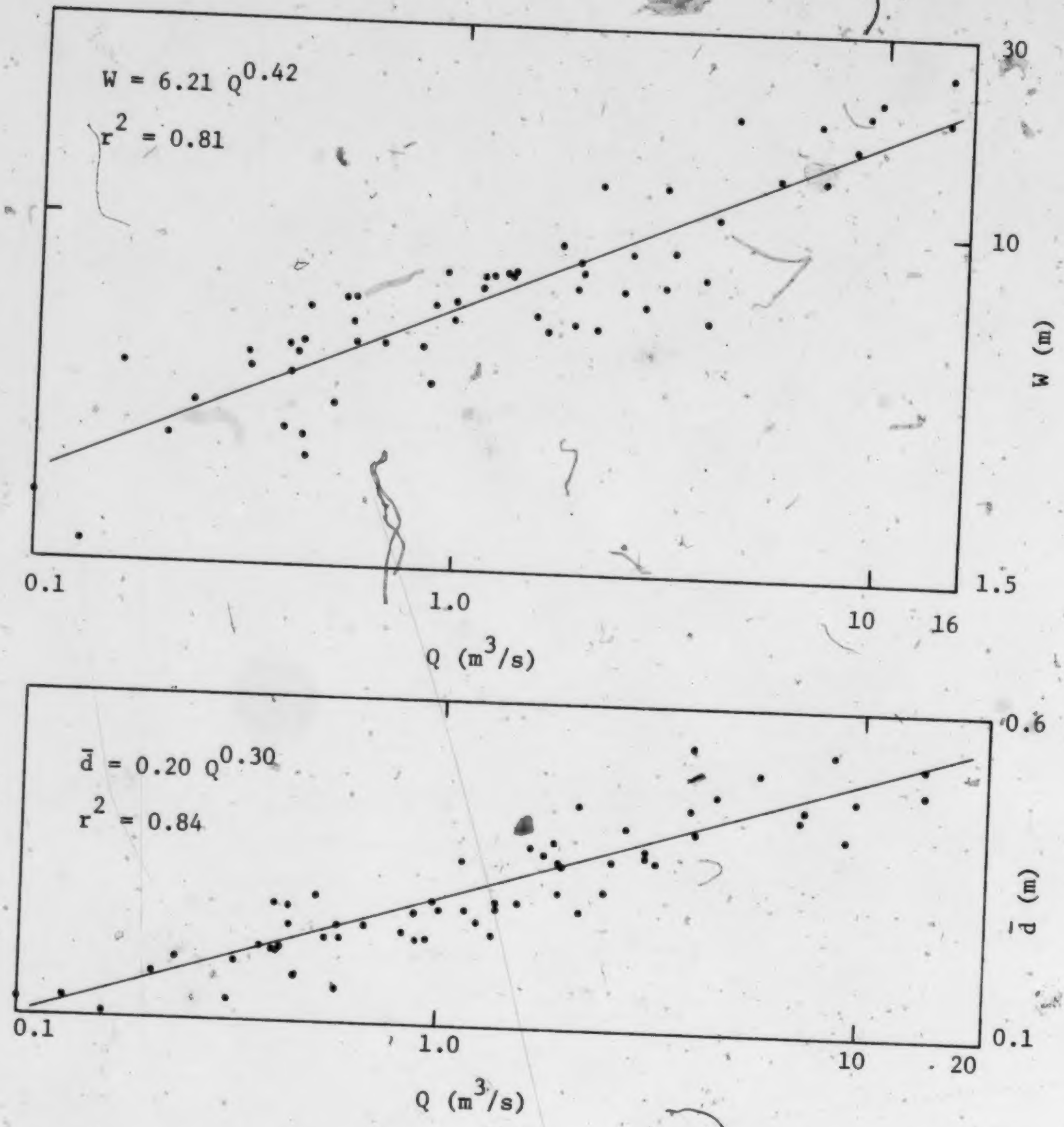
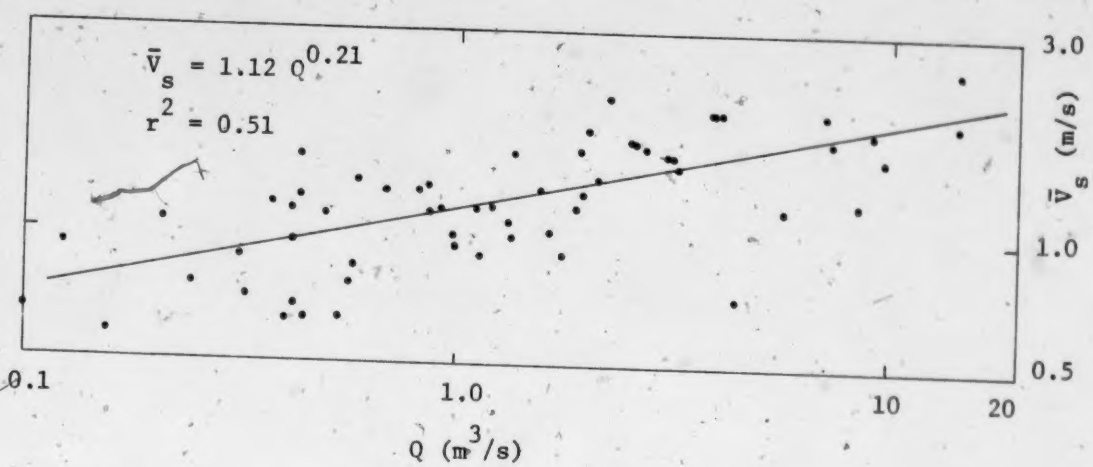
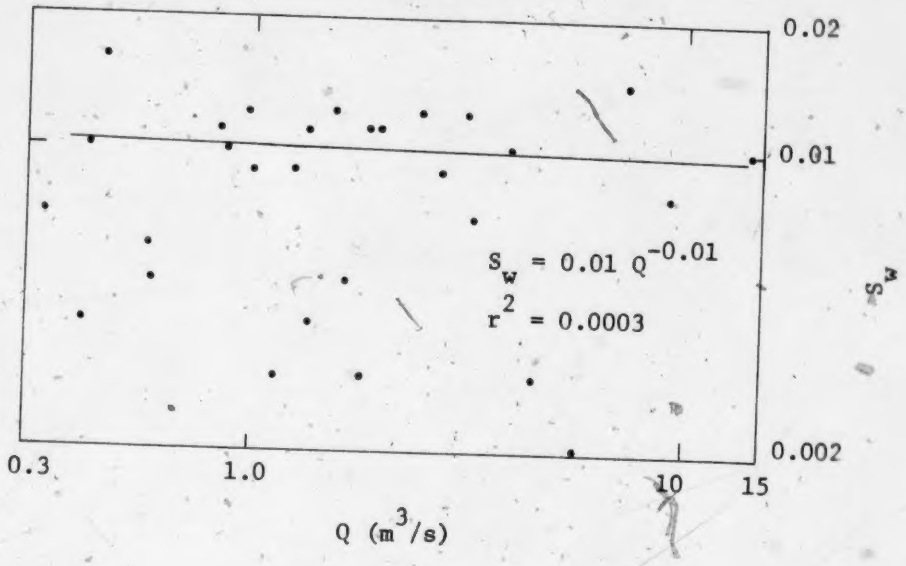


Figure 4-5 D. Log-log plots (4) of the hydraulic geometry relations developed for Beauty Creek Flats as a whole; the subsequent page is included in this figure.


$\bar{V}_s = 1.12\ Q^{0.21}$
$r^2 = 0.51$
3.0
1.0
0.5
$\bar{V}_s$ (m/s)
0.1
1.0
10
20
Q (m^3/s)


0.02
0.01
0.002
S_w
$S_w = 0.01\ Q^{-0.01}$
$r^2 = 0.0003$
0.3
1.0
10
15
Q (m^3/s)

4.2.3 Interpretation Of Downstream Variation In Channel Behaviour

4.2.3.1 Methodology

The interaction between the morphologic and hydraulic parameters that determine a channel's response to a variation in the sediment-water mixture is complex and as Richards (1973, p. 894) states "achieving a point of entry into the system for the purpose of analysis is extremely difficult". One cannot pick a particular parameter or several parameters and state that only these will affect the response of a certain channel characteristic to a variation in discharge. The parameters are thoroughly interrelated. One must choose dominant or control parameters from the available data; those which most adequately explain the variation in that particular channel characteristic. Individually, the parameters may display opposing effects on the channel characteristic being interpreted, that is, some may tend to make it increase with increasing discharge while others would be expected to produce a decrease. It is the dominant parameters which exert the strongest control and which therefore determine the net behaviour of that particular channel characteristic.

In the subsequent section an interpretation is suggested for the downstream variation in each one of the four channel characteristics that were regressed against discharge. As such the interpretation in section 4.2.3.2 is a downstream interpretation as opposed to an at-a-station or at-a-station downstream interpretation (the latter is presented in section 4.2.3.4). The distinction between these types of interpretation was provided in section 1.1.

4.2.3.2 Downstream Hydraulic Geometry

Width

reach	b value
upper	0.39
middle	0.47
lower	0.45

dominant parameters: $\bar{\tau}_o$, $\bar{D}_{50}$

On Beauty Creek Flats the rate of increase of width with increasing discharge increases in the middle reach channels and decreases slightly in the channels of the lower reach. Despite the increase in total discharge in the middle reach due to the discharge contribution from the unnamed creek the concurrent increase in the number of active channels results in an average discharge per channel which is less than that in the upper reach ($2.14\ m^3/s$ vs $3.27\ m^3/s$). In light of the larger b value for the middle reach this would initially seem anomalous, however it can be explained by reference to the $\bar{\tau}_o$ and $\bar{D}_{50}$ values for the upper and middle reach channels. The fact that the middle reach channels are increasing their width at a greater rate indicates that the differential between the τ_b (bank shear stress) and the τ_c (critical shear stress) is larger than it is in the upper reach despite the lower average discharge per channel and the lower $\bar{\tau}_o$ (18.67 kg/m^2 vs 31.69 kg/m^2; average bottom shear stress is taken as representative of average bank shear stress). This is possible due to a marked decrease in the $\bar{D}_{50}$ (decreased by approximately 30%) in the middle reach channels which causes the banks to be more easily eroded (it is assumed that the downstream change in the size distribution of the channel bed is representative of the downstream change in the size distribution of the banks). In short, the $\bar{D}_{50}$ decrease overrides the decrease in the average discharge per channel and average bottom shear stress ($\bar{\tau}_o$) in the middle reach producing a τ_b / τ_c ratio which is larger than it is in the upper reach resulting in a more rapid increase in width. Note that this is the case even though the average width in the middle reach is less than that in the upper reach; ie. more channels of smaller widths as opposed to a few large channels.

In passing from the middle to the lower reach the behaviour of the median grain size ($\bar{D}_{50}$), the average bottom shear stress ($\bar{\tau}_o$) and the average discharge per channel is the same as that which occurred in passing from the upper to the middle reach in as far as the sense of their response is concerned. However, the decrease in $\bar{D}_{50}$ is much greater (57% vs 30%), the decrease in $\bar{\tau}_0$ is less (38% vs 41%) and the decrease in the average discharge per channel is less (6% vs 35%). Rather than suggest a slight decrease in the rate of increase of channel width the data of the lower reach would lead one to expect an increase in the value of b. This would be expec[illegible] since neither the average bottom shear stress (considered to be indicative of the relative magnitudes of the bank shear in the three reaches) nor the average discharge per channel experiences as large a decrease as occurred in the upper to middle reach transition yet the $\bar{D}_{50}$ drops drastically; ie. the erosive energy does not drop as much and the bank material grain size drops by a much greater amount than that which occurred from the upper to middle reach, which should make the banks easier rather than harder to erode. It is suggested that the controlling factor is the percentage of interstitial sand in the bank gravel. Assuming the percentage of sand in the channel grab samples of the theoretical discharge data set is representative of the amount of sand in the channel banks, the increase in the percentage of sand from the upper to the middle reach is approximately 30% (5.41% vs 7.69%) and the increase from the middle to the lower reach is approximately 53% (7.69% vs 16.23%). The ultimate reason for this increase is of course the increasing proximity to the alluvial fan at the bottom of Beauty Creek Flats which lowers the competence of the channels by decreasing the slope. The bank gravel of the middle channels having less interstitial sand would be of a more open work nature and therefore more susceptible to gravity collapse initiated by bank shear and undercutting than the channels of the lower reach. It is felt that the interstitial sand serves a supportive function which becomes a significant factor affecting a slight decrease in the rate of increase of width in the lower reach simply by virtue of its greater abundance. Fahnestock (1963, p. 30) suggests the same role for the interstitial sediment. The sand does not add any cohesiveness but rather holds the gravel size sediment more securely in place by tighter packing.

Briefly stated then, the increased sand percentage more than counterbalances the variation in the other three morphologic/hydraulic factors which occurs in the lower reach and which otherwise would be expected to increase the rate of increase of width.

Average Depth

reach	f value
upper	0.28
middle	0.25
lower	0.36

dominant parameters: $\bar{\tau}_o$, $\bar{D}_{50}$

The average depth-discharge relation for the three reaches of Beauty Creek Flats indicates that the rate of increase of average depth decreases slightly in the middle reach channels and increases markedly in the channels of the lower reach.

The dominant parameters controlling the variation in f down Beauty Creek Flats are felt to be $\bar{\tau}_0$ and $\bar{D}_{50}$. In passing from the upper to the middle reach the $\bar{D}_{50}$ drops by 30% (mentioned above), however the $\bar{\tau}_0$ of the middle reach channels decreases by 41%. This greater decrease in average bottom shear stress is interpreted as overriding the drop in median grain size, resulting in an f value slightly lower than that of the upper reach. In the lower reach a smaller drop in $\bar{\tau}_0$ (38%) and a much larger decrease in $\bar{D}_{50}$ (57%) occurs with the net result being more erodible channel beds and an accompanying increase in the rate of increase of channel depth. If the interpretation is to be viable then one must assume that the increase in the percentage of sand will affect the width response (discussed previously) but not that of depth. Such may be the case since the intensity and consistency of winnowing activity would be greater on the channel beds than on the banks resulting in a relative absence of interstitial fines in the coarse surficial layer of channel bed sediment. This situation is entirely reasonable since the occurrence of armoured beds in gravel streams is a very common phenomenon. The fact that the channel bottom grab samples contained enough sand to make them useful for making inferences as to the percentage of sand in the channel banks (see width interpretation) does not indicate an absence of armouring in these channels. This is a function of the shovel and bucket sampling technique which resulted in a penetration of the channel bed and the incorporation of more than just the armoured surface layer into the sample.

Average Surface Velocity

reach	m value
upper	0.23
middle	0.20
lower	0.15

dominant parameter: S_w

The interpretation of the variation in m down Beauty Creek Flats is straightforward and is an excellent example of the influence of a more dominant factor in controlling the behaviour of a particular channel characteristic. Table 4-1 indicates that the average roughness value decreased down Beauty Creek Flats, a not unexpected response in light of the decrease in $\bar{D}_{50}$. Therefore, if one were to consider only roughness the expected behaviour of m would be to increase down the study area. However, rather than increase from the upper to the lower reach m decreases. This behaviour is attributed to the decreasing value of the water surface slope as the alluvial fan is approached. The water surface slope of the middle reach is only slightly smaller than that of the upper reach (0.010 vs 0.011) and this is reflected in a marginally smaller m value (0.20 vs 0.23). In the lower reach, however, the $\bar{S}_w$ is approximately an order of magnitude less than it is in the middle reach. This decrease is similarly reflected in the m value by a drop to 0.15. Therefore, although velocity increases with increasing discharge in all three reaches the rate of increase is the smallest in the lower reach due to the proximity to the alluvial fan.

A contributing factor to the decrease in m in the middle reach is the decrease in average channel depth of this reach (see table 4-1). The latter decrease is as would be predicted by the Manning equation (see eq. A.4 of appendix A). The average depth remains approximately constant in the lower reach and therefore would not compliment $\bar{S}_w$ in producing a decrease in $\bar{V}_s$.

Water Surface Slope

The slope-discharge relations for Beauty Creek Flats are very poor. This is indicated by the very low values of the coefficient of determination presented in figure 4-5 A to D. For this reason a detailed explanation of exponent variations is not presented. The lack of significance for these regressions indicates that slope is only minimally, if at all, dependent on discharge and that it is therefore, effectively, an independent parameter.

Allowing the water surface slope to be representative of the bed slope (this is justifiable on the basis of the similarity of the two slopes shown in table A-2) the following explanation of the poor correlation between slope and discharge is offered.

In most streams slope is readily adjusted by scour and/or deposition on the channel bed. Such changes usually constitute minor modifications by the stream in an attempt to establish an equilibrium with the sediment-water discharge. On Beauty Creek Flats the slope of the gravel anabranchs is suggested to be in a state of nonadjustment due to the inability of the majority of flows to move the sediment. This inability may be attributed to the coarse nature of the sediment in combination with the low areal slopes of the three reaches due to the establishment of a base level by the alluvial fan at the bottom of Beauty Creek Flats. The degree of nonadjustment of slope can be expected to vary from one anabranch to another. This lack of slope adjustment by discharge is reflected in the large amount of scatter shown on the slope-discharge plots.

On Beauty Creek Flats the slopes of the channels are not a function of discharge. The downstream decrease in slope is a function of increasing proximity to the alluvial fan. The within reach and in particular within transect variation in slope is suggested to be largely due to variations in the size distribution of the channel bed sediment which are in turn the result of variations in the hydraulic characteristics of the channels.

4.2.3.3 Summary Of The Downstream Hydraulic Geometry

The hydraulic geometry relationships developed for the three reaches of Beauty Creek Flats indicate a significant variation in channel response down the study area. The rates of change of width, average depth and average surface velocity were compared using the exponents of the hydraulic geometry relationships. The independent parameter in all cases was water discharge.

Width

The ease of bank collapse in the gravelly alluvium resulted in the primary adjustment to an increasing discharge being an increase in channel width. This is indicated by the higher values of the b exponents in all three reaches.

The rate of increase of width increased from the upper (0.39) to the middle reach (0.47) and decreased slightly from the middle to the lower reach (0.45). The reason for this variation is attributed to a dominant control by a decreasing $\bar{D}_{50}$ in the former case and by an increasing percentage of interstitial fines in the latter.

The fact that the middle reach channels have the largest b value and that coarse material supplied by upstream bank collapse is characteristically transported only several tens of meters downstream in such channels suggests that the highest rate of sediment deposition is occurring in the middle reach. During the period of data acquisition it was obvious that the most active braiding was occurring in this reach. Since deposition of coarse bedload and the resultant deflection of the flow in two directions is a cause of braiding the field observations support the conclusion for the highest sediment deposition rate in the middle reach. Also supporting this conclusion is the fact that the lowest rate of increase of depth (0.25) occurred in the middle reach. The implication here is that the rate of increase of width may be used as an indicator of the intensity of braiding in the gravelly glaciofluvial environment.

In the above context, it is apparent that erodible banks are the primary cause of the braided pattern on Beauty Creek Flats.

Average Depth

In all three reaches the secondary adjustment to an increase in discharge was by an increase in average channel depth as the f values indicate. The rate of increase in average depth decreases from the upper (0.28) to the middle reach (0.25) and increases considerably in the lower reach (0.36). The controlling parameters over this variation are suggested to be average bottom shear stress ($\bar{\tau}_0$) and average grain size ($\bar{D}_{50}$). The net behaviour of average depth is determined by the relative magnitude of the decrease in these two parameters which occurs in passing from the upper to the middle reach and from the middle to the lower reach. In the former transition the decrease in average bottom shear stress (41%) exceeds the drop in $\bar{D}_{50}$ (30%) producing the smaller f value in the middle reach. In the middle to lower reach transition the reverse occurs and the drop in $\bar{D}_{50}$ (57%) exceeds the decrease in average bottom shear stress (38%) which allows the rate of increase of average depth to increase. The percentage of interstitial fines is not considered important in determining the depth response due to their removal from the surficial layer of coarse channel bed sediment by winnowing which results in an armoured bed.

Average Surface Velocity

In all three reaches the tertiary adjustment to an increasing discharge is an increase in the average surface velocity of the channels. The rate of increase of average surface velocity decreases from the upper (0.23) to the middle reach (0.20) and from the middle to the lower reach

(0.15). The dominant influence over this progressive decrease is the decrease in average water surface slope down Beauty Creek Flats created by the alluvial fan at their downstream end which restricts the flow to one channel and creates a local base level for the upstream channels. A small difference between the average slopes of the upper and middle reaches (0.011 and 0.010 respectively) produced the similarly small decrease in the m value in the middle reach and an approximate order of magnitude difference between the average water surface slopes of the middle and lower reaches caused the larger drop in the m value in the lower reach. The smaller values of these velocity exponents relative to the m values obtained in such hydraulic geometry studies as that by Leopold and Maddock, 1953 and Wolman, 1955 whose average m values were 0.34 and 0.55 respectively, is a further indication of the relative instability of the Beauty Creek Flats channels (see Rhodes, 1977, p. 80).

Slope

The very low correlation for the slope-discharge power function relations developed for Beauty Creek Flats indicates that slope may be considered as an independent parameter.

Slope is suggested to be in a state of nonadjustment due to the inability of most of the flows transmitted by the channels to move the coarse gravelly sediment.

The downstream decrease in slope is attributed to an increase in proximity to the alluvial fan at the bottom of Beauty Creek Flats and a within reach and within transect variation is suggested to be mainly due to variations in the size distribution of the channel bed sediment.

4.2.3.4 At-A-Station Downstream Hydraulic Geometry

In section 1.1 the difference between downstream and at-a-station hydraulic geometry was explained as a difference arising from the consideration of the downstream variation in the channel characteristics individually in the former case as opposed to considering the variation in the response of the characteristics cumulatively in the latter. At-a-station downstream hydraulic geometry is simply the comparison of various stations along the length of a river. The object of this section is not to offer an additional explanation for the variation in channel behaviour down Beauty Creek Flats but rather by considering each of the three reaches as stations (discussed previously on p. 70) to distinguish graphically the channel behaviour in each reach through the use of the b-f-m diagram of Rhodes (1977). This diagram is a triangular plot of the values of the b, f, and m exponents and was developed by Rhodes to aid in the interpretation of the variation displayed by hydraulic geometry relationships. Rhodes's b-f-m diagram is presented below as figure 4-6, p. 101. The interpretative potential of the diagram arises from Rhodes's division of it into ten

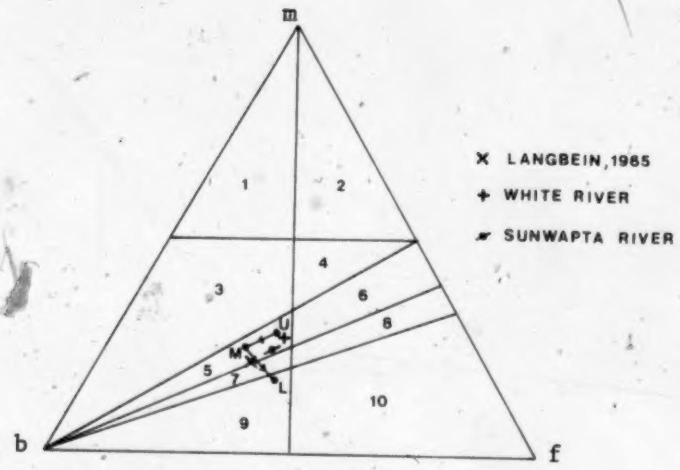


Figure 4-6. The b-f-m diagram of Rhodes (1977, fig. 7). Rhodes's divison of the diagram into ten channel types aids the downstream at-a-station interpretation of channel change. The variation in channel response to an increasing discharge down Beauty Creek Flats is indicated by the plotting position of the upper, middle and lower reach. Also shown is the plotting position for Langbein's theoretical b, f and m values for noncohesive channels, the point representing the Sunwapta River at Beauty Creek Flats and the point representing the White River of Fahnestock, 1963.

channel types (numbered) using five criteria drawn mainly from Leopold and Maddock's 1953 publication. These criteria are represented by the five lines on the diagram. The interpretative implications of each of these divisions is discussed in detail in Rhodes's publication.

The presentation of this diagram serves two purposes. Firstly, as mentioned above it allows a graphical demonstration of the variation in channel behaviour between the three reaches of Beauty Creek Flats. Secondly, by plotting the position of the three reaches on it and comparing the channel behaviour predicted by the diagram (see Rhodes's table 2, p. 82) to the actual channel behaviour the interpretative power of the diagram can be tested.

Use of the diagram requires that the b, f and m values sum to unity as dictated by the identity $Q = wdv$. However, in the majority of cases they do not (see Rhodes, 1977, p. 75). In order to plot on the diagram the values of b, f and m must be adjusted so that they do equal unity. The adjustment procedure used here is that used by Rhodes on p. 75. Rhodes felt that errors in measurement of depth and in particular velocity were more likely than errors in width measurement and therefore adjusted only the f and m exponents. The sum of the b, f and m exponents for the upper, middle and lower reach of Beauty Creek Flats are 0.90, 0.92 and 0.96 respectively. For the purpose of plotting on the b-f-m diagram the f and m values are increased by 0.05 each in the upper reach, f is incremented by +0.03 and m by +0.05 in the middle reach and both f and m are increased by 0.02 in the lower reach. The change in the plotting position of the adjusted exponents relative to the unadjusted exponents is very small but as Rhodes (1977, p. 75) emphasized, since adjustments were made the positions of the points can only be considered as close approximations of the correct locations. Included on the diagram is the plotting position for noncohesive channels determined by using the theoretically derived b (0.48), f (0.30) and m (0.22) values of Langbein (1965, p. 306), the plotting position of the White River channels (Fahnestock, 1963) and the plotting position for Beauty Creek Flats whose b, f and m values are 0.42, 0.30 and 0.21 respectively. For plotting on the b-f-m diagram the f and m exponents for Beauty Creek Flats are adjusted by +0.03 and +0.04 respectively. The White River, Beauty Creek Flats and Langbein's theoretical b-f-m values plot as a type 5 channel.

Figure 4-6 shows that the channels of the upper and middle reach plot as type 5 channels while the channels of the lower reach plot as type 9. As such the points lie in the region of the diagram which Rhodes considered to be indicative of braided rivers (see Rhodes, figure 5, p. 86). Rhodes (1977, table 2, p. 82) has tabulated the response predicted for a type 5 and type 9 channel with respect to the change in four channel parameters with increasing discharge. Table 4-3 presented below compares the response of these parameters to an increasing discharge as predicted by the b-f-m diagram for channel types 5 and 9, to their actual response in the upper, middle and lower reach. The bracketed number after the response is the exponent value determined for that particular power function relation. As the table shows the predicted response of the channel parameters is exactly that which actually occurred for all three reaches. This is considered to be strong evidence of the interpretative ability of the b-f-m diagram in hydraulic geometry studies of channel change.

In summary, an at-a-station downstream hydraulic geometry plot of the three reaches of Beauty Creek Flats

channel type	channel parameter	response predicted from b-f-m diagram	actual response	
			upper reach	middle reach
5	width/depth	increases	increases (0.12)	increases (0.22)
	Froude number	increases	increases (0.10)	increases (0.12)
	velocity/area	decreases	decreases (-0.46)	decreases (-0.50)
	$S^{\frac{1}{2}}/n$	increases	increases (0.07)	increases (0.12)
			actual response of lower reach	
9	width/depth	increases	increases (0.09)	
	Froude number	decreases	decreases (-0.03)	
	velocity/area	decreases	decreases (-0.68)	
	$S^{\frac{1}{2}}/n$	decreases	decreases (-0.17)	

Table 4-3. The response of channel parameters to an increasing discharge as predicted from Rhodes's b-f-m diagram and as actually occurred on the three reaches of Beauty Creek Flats. The numbers in brackets are the exponents of the power functions.

indicates a change from a type 5 channel to a type 9 channel as defined by Rhodes's b-f-m diagram. The plot (see figure 4-6) indicates that the middle reach channels although belonging to the same channel type as the channels of the upper reach are distinguished by a larger b/f ratio and a smaller m value. The lower reach channels have approximately the same b/f ratio as the upper reach and are distinguished primarily by a low rate of increase in velocity with discharge, or in other words a significantly smaller m value.

4.2.4 Best Fit Equations For Beauty Creek Flats

Equations 4.13 to 4.16, p. 78, determined for the collated Beauty Creek Flats data were not necessarily the most appropriate mathematical model of the relationships between the dependent variables and discharge. As stated in section 1.1, power functions are the conventional model used in the hydraulic geometry approach to channel change. To determine if other models would provide a better comparison between the observed and predicted values of the dependent variable, polynomials up to and including the second order were tested. Strictly speaking these may not be considered the best fit equations since successively higher order terms up to N-1 could be added to improve the predictive ability of the model. The cutoff at the second order term was based on practicality as well as on conceptual grounds. In the latter context, since the dominant discharge was approximately bankfull and the range of stage during the hours of the day when the data was gathered was reasonably limited, not even quadratic behaviour would be expected from any of the dependent variables. This expectation was proven to be correct by the model testing. The best mathematical model for width, average depth and average surface velocity turned out to be the power functions presented as equations 4.13 to 4.15 inclusive, p. 78, while that for water surface slope was of the general form $y = \bar{y}$. That this is the best model for water surface slope is not surprising in light of the very low slope (-0.01) and r^2 value of its power function (see equation 4.16).

Of the best fit models the most statistically sound are equations 4.13 and 4.14. The choice of the most statistically sound was based on the value of the coefficient of determination (r^2) and on the appearance of the residuals plot. To be accepted the residuals plot had to display a roughly tabular pattern and the r^2 values had to exceed 0.80 at a 5% level of significance. Only the width (eq. 4.13) and average depth (eq. 4.14) equations met these criteria. The standard error for these equations, in log units, is 0.108 and 0.069 respectively.

Since the models chosen are both power functions it would seem worthvile to briefly examine the conceptual and technical difficulties associated with their usage and in particular to determine the applicability of these difficulties to the gravel channels examined on Beauty Creek

Flats. These difficulties were discussed by Thornes (1977). They are (1) indeterminacy of channel response (2) nonequilibrium flow conditions (3) discontinuity in response and (4) nonlinearity in response. The former two are not unique to power functions but rather are conceptual difficulties associated with channel change and river hydraulics in general. One must be aware of them but their solution awaits the development of a more precise and thorough theoretical understanding of open channel flow. For the latter two, the problem associated with the use of power functions arises from their log-linear representation of the river channel relations. Usually this is an oversimplification of the relationships as discontinuities or nonlinear response in the dependent parameter is often observed. With reference to discontinuity, it was explained that a break in the roughness-discharge plots (a similar break would therefore be expected for velocity and depth -discharge plots) occurs at the change from subcritical to supercritical flow which is attributable to a sudden reduction and then increase in form resistance associated with the destruction and creation of dune bed forms. Such scour activity is usually restricted to sand bed channels and as such discontinuity in response is considered to be nonapplicable to the gravel channels of Beauty Creek Flats. Most hydraulic geometry data is gathered from subcritical flows and therefore such discontinuities usually are not important considerations. Nonlinearity in response results from changes in the rate of increase or decrease (slope) of the dependent variable due to either a sudden, drastic variation in flow conditions or abrupt changes in the cross sectional geometry of the channel with rising or falling stage (see Richards, 1976) or both. The nonapplicability of this situation to the collated Beauty Creek Flats data has already been demonstrated by virtue of the fact that second order polynomials did not fit this data significantly better than the log-linear power functions. As explained above, this is the result of the lack of very large fluctuations in stage during the time of the day that data was acquired; ie. fluctuations which would approximate one half or more of average channel depth.

In summary, as a result of the coarse nature of the Beauty Creek Flats channels and due to the dominant discharge range (approximately bankfull) at the time of data acquisition discontinuities or nonlinearity in the response of the dependent parameters did not occur. The result is that the log-linear power function representation of the relationships do not constitute severe oversimplifications. Therefore, their utility as estimators of channel response to varying discharge is at a maximum under these flow conditions.

4.3 Comparison Of The Beauty Creek Flats Channels To Channels From Other Gravelly Glaciofluvial Environments

4.3.1 Introduction

In classifying hydraulic geometry data sets according to climate Park (1977) included the studies of Nordseth (1973) and Brush (1961) in the proglacial category. However, reference to these publications indicates that the rivers of neither are currently proglacial and are therefore not comparable to the Sunwapta River. The most recent major study of fluvial processes in the proglacial environment was done by Church (1972) on Baffin Island sandar. The mean hydraulic geometry exponents for width, depth and average velocity on these sandar are provided in table 25, p. 186 of Church's publication. Also included in this table were the width, depth and average velocity exponents from Arnborg's 1955 study of the Hoffellssandur (computed by Church from Arnborg's data) and the same exponents from Fahnestock's 1963 study of the White River, Mount Rainier, Washington, U.S.A. Although they are all studies of the gravelly, glaciofluvial environment the former two differ from the latter one with respect to the manner in which the channel data was acquired. Church and Arnborg's exponents were determined from successive flow measurements at one (Arnborg) or a number of gauging stations on the sandur(s) (Church) and as such represent at-a-station hydraulic geometry exponents. In contrast to this the hydraulic geometry exponents of Fahnestock's study were derived from single flow measurements at many different stations on the White River valley train. As was mentioned previously, Fahnestock (1963, p. 13) indicated that this approach could be considered analogous to gathering channel data from a number of cross sections in the vicinity of a particular gauging station. As such this methodology may be considered as a cruder form of the at-a-station hydraulic geometry approach to channel change.

The methodology used to acquire the channel data for the Sunwapta River at Beauty Creek Flats was the same as that used by Fahnestock and for this reason only his study is strictly comparable.

4.3.2 Comparison To The Channels Of The White River

Fahnestock, over a period of two years (1958 and 1959) collected data on 112 channels from an approximately 1.3 km stretch of the White River between the confluence of west and east Emmons Creek and the point where the river is restricted to a single channel by a moraine. In addition to being smaller than Beauty Creek Flats (9 km) the White River study area did not have any major tributaries (see Fahnestock's figure 1 and 3, p. 3 and 7). In order to have as thorough a comparison as possible ten parameters from Fahnestock's table 7, p. 62 (grain size data taken from table 2, p. 24) were converted to metric and reduced to their summary statistics. This data is presented below as table 4-4, p. 111. Comparison of this data to the data on

parameter	$\bar{X}$	std. dev.	min/max	N
flow area (m^2)	1.70	1.36	0.002/5.64	112
S_w	0.023	0.014	0.002/0.062	69
w (m)	5.62	3.28	0.21/18.29	112
$\bar{d}$ (m)	0.24	0.14	0.01/0.63	112
w:d	24.76	10.28	10/71	112
$\bar{V}_{xs}$ (m/s)	1.12	0.59	0.09/2.74	112
Fr	0.72	0.23	0.24/1.51	112
n	0.057	0.080	0.013/0.085	69
D_{50} (mm)	158.38	24.98	120/180	8
Q (m^3/s)	2.55	2.51	0.0003/12.18	112

Table 4-4. Statistical summary of the White River channel characteristics of Fahnestock's 1963 study.

the 60 channels of Beauty Creek Flats contained in table 4-1 indicates a high degree of similarity between the two areas. Of the ten parameters compared the mean values for area, width, width to depth ratio and average velocity on the Sunwapta exceeded the corresponding values for the White River. For water surface slope, Froude number, roughness, discharge and grain size (D_{50}) the average value of the White River was greater than its counterpart on the Sunwapta. The greatest difference between the two areas lies in the mean values for slope (0.023 vs 0.008), Froude number (0.72 vs 0.66) and grain size (White River vs Sunwapta River). It should be noted that the average velocity data for the White River is the average cross section velocity acquired during discharge measurements whereas the average velocity for the Sunwapta is a surface velocity. Also, a strictly valid comparison is not possible for grain size since his D_{50} data (see his table 2, p. 24) on the study area mentioned above consisted of only eight data points obtained by pebble counts of material greater than 4 mm in diameter (the method of Wolman, 1954, was used) located on subaerial, central portions of the valley train. As mentioned previously, the grain size data for Beauty Creek Flats represents grab samples taken from the channel bed. The work of Ballantyne (1975, 1978) on an Ellesmere Island sandur and Smith (1974) on the valley train of the Kicking Horse River in British Columbia indicates that the channel deposits are coarser than adjacent bar sediment. This suggests that despite the difference in sampling technique and sample location the D_{50} of the White River channels are considerably coarser. Also supporting this inference are Fahnestock's comments on boulder movement in the remarks column of his table 7. No such movement or sediment occurred on Beauty Creek Flats.

The greatest similarity between the two rivers is found in the mean values for the average depth (0.24 vs 0.23 m) and discharge data (2.55 vs 2.47 m^3/s; White vs Sunwapta).

An hypothesis test for the comparison of two sample means using the discharge means of the two areas resulted in the acceptance of the null hypothesis (equal population means) at an alpha level of 0.005. This indicates that the discharge data of the White River could have been obtained from Beauty Creek Flats of the Sunwapta River and vice versa. They are statistically the same population.

In addition to being similar with respect to the ten parameters mentioned above the two areas are also very comparable in terms of most of their hydraulic geometry exponents (slope exponents excepted; see table 4-5). Of the five relations for the White River, three (width, depth and velocity) were determined by Fahnestock and two (roughness and slope) were determined from his data in table 7 for the purpose of comparison.

The similarity of the exponents in light of the large difference in average slopes between the two areas suggests that slope is not an important determining parameter of channel behaviour in these two areas. This also suggests that slope may have been an independent parameter in the White River channels as it has been interpreted to be in the channels of Beauty Creek Flats.

4.3.3 Comparison To Channel Behaviour In Other Gravelly Glaciofluvial Areas

Table 4-5 presented below gives the hydraulic geometry exponents determined for the Sunwapta River at Beauty Creek Flats and those determined for the White River (Fahnestock, 1963), Baffin Island Sandar (Church, 1972) and the Hoffellssandur (Arnborg, 1955). Examination of this table

	exponent				
source	W	d	$\bar{V}$	n	S_w
Baffin Island sandar, Church (1972)	0.22	0.31	0.48	/	/
Hoffellssandur, Arnborg (1955)	0.17	0.39	0.44	/	/
White River, Fahnestock (1963)	0.38	0.33	0.27	0.01	0.13
Sunwapta River at Beauty Creek Flats	0.42	0.30	0.21	-0.01	-0.01

Table 4-5. Comparison of the exponents of the hydraulic geometry relations determined for the Sunwapta River at Beauty Creek Flats to the corresponding exponents of the hydraulic geometry relations determined for similar glaciofluvial enviroments.

indicates that for the gravel channels of the Baffin Island Sandar and the Hoffellssandur the primary adjustment to an increasing discharge is a rapid increase in velocity, whereas for the gravel channels of this study and those of the White River the primary adjustment to an increasing discharge is an increase in channel width. Reference to Rhodes's (1977) figure 5, p. 86 indicates that the channel behaviour of the former two is anomalous for braided channels which in almost all cases plotted on the left half of the b-f-m diagram (as did the channels of the Sunwapta and White River). This is a significant variation in channel behaviour within the same fluvial environment. Possible reasons for this variation are discussed in the remainder of this section.

In order to be able to increase their velocity so rapidly the flow resistance in the channels of Church and Arnborg's studies must decrease very sharply with an increasing discharge (Church determined that the exponent of the Darcy-Weisbach friction factor-discharge power relation was equal to -0.65). Church attributes this rapid decrease primarily to a rapid increase in the sediment load at high discharges which would smooth out the roughness of the channel bed and reduce turbulence through an increase in the viscosity of the sediment-water mixture. Unfortunately, the rate of increase of sediment load was not investigated in this study and is not known for either Fahnestock's or Arnborg's study. As such it cannot be determined whether this can account for the variation in channel behaviour between the two groups. However, one would expect that in any gravelly proglacial braided river a relatively rapid increase in sediment load would accompany the rapid increase in discharge that characterizes these rivers. It is suggested that some other factor which is common to Church's and Arnborg's studies but not to this and Fahnestock's is responsible for the variation in channel behaviour. This common factor is suggested to be the low temperatures of high arctic summer nights. Church's figure 15 indicates that freezing temperatures frequently occurred during June, July and August at Ekalugad Fiord and from data gathered at three climatological stations on east central Baffin Island from 1959 - 1968 he determined that June's mean temperature may have exceeded zero degrees Celsius only approximately 25 % of that time (p. 13). Table 4-5 indicates that the difference between the Arctic and non-Arctic studies is the magnitude of the width and velocity exponents, the depth exponent being similar in all four studies. The Arctic channels experienced much lower rates of change of width and much higher rates of change of velocity. If freezing nocturnal temperatures are to account for this anomalous behaviour of the Arctic channels it must be able to explain the changes in these exponents. Low width and high velocity exponents indicate a higher bank stability which the freezing temperatures must therefore be able to explain. Why freezing temperatures would not affect the depth exponent must also be explained.

It is suggested that a greater bank stability is caused by freezing of intergranular films and pockets (interstitial) of water in the exposed, wet, bank sediment during the night when the stage has dropped. Thawing during the following day would often be incomplete due to a very small temperature variation (also indicated by Church's figure 15 and mentioned on his p. 13). Incomplete thawing would be aided by the low thermal conductance of the gravel. The result would be banks which are more resistant to erosion than non-cohesive banks in southern latitudes. This would cause a low rate of increase of channel width and channels unable to accomodate an increase in discharge by increasing their width will either increase their depth or velocity in an attempt to maintain within channel flow. Of the two, an increase in velocity represents the least work for a channel flowing in gravelly alluvium resulting in it being the primary adjustment to an increased discharge in these Arctic channels. The channel banks of this and Fahnestock's study were not subjected to this freezing and as a result their primary adjustment is an increase in width due to the ease of gravel channel bank collapse.

The rate of change of depth of the Arctic channels is not affected by the freezing temperatures due to the insulating effect of the channel water which prevents the channel bed sediment from freezing. This accounts for the similarity in the depth exponents among the four studies of table 4-5.

The similarity of the hydraulic geometry exponents between this study and Fahnestock's and between Church's and Arnborg's studies suggests that gravelly proglacial braided channels behave similarly provided the associated climatic conditions are similar. It is therefore reasonable to suggest equations for estimative usage on areas of gravelly braided outwash other than those included in table 4-5. Such equations could also be used for estimating the paleoflow characteristics of the channels in/on exposed, ancient, gravelly braided outwash.

Since Church's study is the only major study of braided gravel outwash in the Arctic climate his width and velocity equations are suggested for estimating channel response to an increasing discharge in this climate. In the non-Arctic climate, the only two are this study and that of Fahnestock (1963). The choice of equations for estimative usage from these two studies is based on the value of the coefficient of determination. In this context, the width and velocity equations of Fahnestock were chosen.

Since the depth response did not vary significantly between the Arctic and non-Arctic studies the depth relation with the best coefficient of determination was chosen for estimative usage in both climates. The depth relation of this study was chosen on this basis.

4.4 Conclusions

The investigation of the active gravel channels on Beauty Creek Flats of the Sunwapta River has resulted in the following conclusions which have been grouped into three categories.

Conclusions Applicable To Gravelly Braided Outwash In General

1. There is a similarity in channel response to an increasing discharge in the gravelly glaciofluvial environment provided the associated climatic conditions

(specifically temperature) are similar.

2. It is suggested that the larger velocity exponent and lower width exponent of braided gravel outwash in an Arctic climate may be due to a greater bank stability caused by freezing of the channel bank sediment during the night when the stage has dropped.
3. The width and velocity equations of Church (1972, p. 186) and the depth relation of this study are suggested for estimating gravelly glaciofluvial channel response in an Arctic climate. In the non-Arctic climate the depth relation of this study (eq. 4.14) and the width and velocity equation of Fahnestock (1963) are suggested for similar usage.
4. The rate of change of depth with an increasing discharge in braided gravel outwash is similar in Arctic and non-Arctic climates. The depth relation of this study is suggested for estimative usage.
5. The rate of increase of width with increasing discharge (b exponent) may be used as a braiding intensity index.

Conclusions From Channel Data On Beauty Creek Flats

1. A variation in channel behaviour does exist between an upper, middle and lower reach of Beauty Creek Flats.
2. The most influential parameter affecting this variation

is the median grain size (D_{50}) of the channel bed and banks which decreases downstream.

3. In all three reaches of Beauty Creek Flats the primary, secondary and tertiary adjustment of the channels to an increase in discharge is an increase in width, depth and velocity respectively.
4. Bankfull flow exceeds the critical condition required for significant gravel movement in all three reaches.
5. The highest rate of sediment deposition occurs in the channels of the middle reach.
6. The alluvial fan at the lower end of Beauty Creek Flats exerts a dominant control only over the velocity-discharge relation.
7. The upstream growth of the grassy area located immediately below the lower reach has been caused by more frequent overbank activity in this area of Beauty Creek Flats.
8. Under the conditions of this channel study (gravel bed and banks and a limited fluctuation in stage around the bankfull condition) power functions are good predictors of channel behaviour.
9. Rhodes's (1977) b-f-m diagram provided an accurate prediction of channel response to an increasing discharge for the channels of this study.
10. The channels of the middle reach are distinguished from the upper reach channels by a larger b/f ratio and a smaller m value. The lower reach channels are

distinguished from those of the upper and middle reach by a significantly smaller m value.

Conclusions From Observations On Beauty Creek Flats

1. The channels in the active flow areas of Beauty Creek Flats are very unstable. The major cause of braiding is erodible banks.
2. Significant gravel movement on Beauty Creek Flats occurs during only two periods of the year. These are in the spring, during runoff, and in the summer during peak discharge.
3. As a whole, Beauty Creek Flats is neither aggrading or degrading. Its sediment is simply being reworked.

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Appendix A

The measured discharge data set (table A-1), the theoretical discharge data set (table A-2) and table A-3 are presented in this appendix. Tables A-1 and A-2 contain the data used to develop the hydraulic geometry relations for the Sunwapta River at Beauty Creek Flats. The details of the field procedure used for each data set are found on p. 43 - 47. With reference to tables A-1 and A-2 several points should be noted.

1. The variability of the gravel to sand ratio contained in table A-2 is a reflection of the crudeness of the shovel and bucket sampling technique employed. However, the decreasing downriver trend of this ratio shown in table 4-1 demonstrates that the channel bed samples so obtained are still representative despite the variability.
2. For one channel (channel 6/1) of table A-2 the water surface slope was zero due to balancing positive and negative gradients along the channel. In this situation the bed slope was used for any calculations requiring the use of slope data.
3. For the calculation of the channel Reynolds number for the channels of the measured discharge data set the average kinematic viscosity for the upper (transects 1 and 2), middle (transects 3, 4 and 5) and lower reach (transects 6 and 7; see figure 1-3) of the theoretical discharge data set was determined and used.

4. The flow area of table A-1 represents the quotient of discharge over the average flow cross section velocity as determined by current meter measurements. For the channels of table A-2 no such velocity was obtained and the flow area was determined by dividing discharge by the average velocity at 0.6 of the depth.

The standard equations used for the calculation of the channel Reynolds number (Re_{ch}) and Froude number (Fr) of table A-1 and A-2 and for the average bottom shear stress ($\bar{\tau}_o$) and Mannings n of table A-2 are presented below.

$$\bar{\tau}_o = \gamma_f R S \qquad \text{Eq. A.1}$$

where $\gamma_f = \rho g$

$R = \bar{d}$

$S = S_w$

$$Re_{ch} = \frac{\bar{V} R}{\nu} \qquad \text{Eq. A.2}$$

where $\bar{V} = \bar{V}_{0.6}$

$R = \bar{d}$

$\nu = \mu/\rho$

$$Fr = \frac{\bar{V}}{(gd)^{\frac{1}{2}}} \qquad \text{Eq. A.3}$$

where $\bar{V} = \bar{V}_{0.6}$

$d = \bar{d}$

$$n = \frac{R^{0.67}\ S^{0.50}}{V} \qquad \text{Eq. A.4}$$

where $R = \bar{d}$

$S = S_w$

$V = \bar{V}_{xs}$

Note: The average cross section velocity of the theoretical discharge data set was derived from the average, average surface velocity to average cross section velocity ratio (1.67) determined from the data of the measured discharge data set.

TABLE A - 1. THE MEASURED DISCHARGE DATA SET

reach	ch.	date	width (m)	av. depth (m)	w:d	flow area (m^2)	$\bar{V}_{xs}$ (m/s)	$\bar{V}_s$ (m/s)	$\bar{V}_{0.6}$ (m/s)	Fr	Re_{ch}	Q (m^3/s)
upper	1	Aug. 12	4.27	0.19	22.47	0.87	0.47	1.16	0.90	0.66	116327	0.41
	2	12	5.79	0.34	17.03	1.95	1.11	2.08	1.46	0.80	337687	2.17
	3	12	8.69	0.25	34.76	2.22	1.16	1.65	1.41	0.90	239796	2.58
	4	12	5.18	0.17	30.47	0.95	0.61	1.31	0.99	0.77	114490	0.58
	5	13	10.97	0.30	36.57	3.34	1.24	1.91	1.51	0.88	308163	4.14
	6	13	3.05	0.13	23.46	0.37	0.57	1.07	0.75	0.66	66327	0.21
	7	13	7.32	0.25	29.28	1.88	1.02	1.77	1.26	0.80	214286	1.92
	8	13	24.38	0.38	64.16	9.86	1.48	2.44	1.98	1.03	511837	14.59
	9	13	3.66	0.14	26.14	0.53	0.45	0.75	0.56	0.48	53333	0.24
	10	13	5.18	0.17	30.47	0.84	0.80	1.27	1.09	0.84	126054	0.67
middle	1	14	3.05	0.17	17.94	0.55	0.80	1.24	0.99	0.77	121957	0.44
	2	14	21.03	0.36	58.42	7.82	1.25	1.52	1.38	0.73	360000	9.78
	3	14	3.20	0.15	21.33	0.45	0.84	1.19	0.80	0.66	86957	0.38
	4	14	8.38	0.21	39.90	1.92	1.02	1.58	1.50	1.05	228261	1.96
	5	14	2.13	0.11	19.36	0.22	0.37	0.66	0.46	0.44	36667	0.08
	6	14	12.80	0.19	67.37	2.43	0.90	1.38	1.03	0.75	141812	2.19
	7	14	7.93	0.19	41.74	1.57	0.88	1.51	1.15	0.84	158333	1.38

TABLE A - 1. (continued)

reach	ch.	date	width (m)	av. depth (m)	w:d	flow area (m^2)	$\bar{V}_{xs}$ (m/s)	$\bar{V}_s$ (m/s)	$\bar{V}_{0.6}$ (m/s)	Fr	Re_{ch}	Q (m^3/s)
middle	8	Aug. 14	2.74	0.19	14.42	0.49	0.89	1.51	1.12	0.82	154203	0.44
	9	13	6.40	0.16	40.00	1.11	0.79	1.31	1.10	0.88	127536	0.88
	10	13	7.86	0.34	23.12	2.54	1.55	1.98	1.73	0.95	426232	3.93
lower	1	14	7.62	0.16	47.63	1.27	0.74	1.17	0.77	0.61	91940	0.94
	2	14	3.66	0.20	18.30	0.75	0.68	1.10	0.80	0.57	119403	0.51
	3	14	6.55	0.16	40.94	1.04	0.52	0.64	0.58	0.46	69254	0.54
	4	14	7.62	0.25	30.48	1.89	0.61	1.13	0.80	0.51	149254	1.15
	5	15	1.68	0.11	15.27	0.19	0.69	0.90	0.61	0.59	50075	0.13
	6	15	4.57	0.10	45.70	0.50	0.32	0.58	0.53	0.54	39552	0.16
	7	15	12.80	0.26	49.23	3.22	0.96	1.51	1.17	0.73	227015	3.09
	8	15	5.18	0.15	34.53	0.96	0.45	0.95	0.75	0.62	83955	0.43
	9	15	18.29	0.33	55.42	7.46	0.94	1.91	1.55	0.86	381716	7.01
	10	15	4.88	0.11	44.36	0.58	0.55	0.87	0.63	0.61	51716	0.32

TA

			width (m)			av. depth (m)			width:depth			
tr.	ch.	date	upper	middle	lower	upper	middle	lower	upper	middle	lower	fl
1	1	Aug. 4	9.45	14.33	16.61	0.41	0.33	0.30	23.05	43.42	55.37	
	2	4	5.33	4.88	11.28	0.17	0.27	0.23	31.35	18.07	49.04	
	3	4	3.81	X	8.23	0.57	X	0.40	6.68	X	20.58	
	4	4	3.05	4.57	10.67 *	0.25	0.20	0.14*	12.20	22.85	X *	
	5	4	6.40	10.06	5.79	0.20	0.28	0.33	32.00	35.93	17.55	
2	1	5	1.83	6.28	6.40	0.16	0.13	0.15	11.44	48.31	42.67	
	2	5	7.32	7.77	8.53	0.27	0.26	0.21	27.11	29.89	40.62	
	3	5	4.27	5.33	7.93	0.22	0.19	0.19	19.41	28.05	41.74	
	4	5	7.01	6.25	4.57	0.14	0.27	0.43	50.07	23.15	10.63	
	5	5	18.29	X	19.51	0.48	X	0.41	38.10	X	47.59	
3	1	6	5.18	8.69	5.94	0.15	0.17	0.26	34.53	51.12	22.85	
	2	6	23.62	18.75	16.15	0.27	0.29	0.34	87.48	64.66	47.50	
4	1	7	5.94	7.62	9.14	0.21	0.15	0.17	28.29	50.80	53.77	
	2	7	3.51	5.18	3.81	0.20	0.16	0.22	17.55	32.38	17.32	
	3	7	7.01	7.47	9.14 *	0.17	0.16	0.17*	41.24	46.69	X *	

1 of

TABLE A - 2. THE THEORETICAL DISCHARGE DATA SET

pth		channel									
le	lower	flow area (m^2)	length (m)	S_w	S_b	$\bar{w}$	$\bar{d}$	av. w:d	$\bar{V}_s$ (m/s)	$\bar{V}_{0.6}$ (m/s)	$\bar{\tau}_o$ (k
2	55.37	5.59	167.64	0.014	0.013	13.46	0.35	40.61	1.69	1.32	48.0
7	49.04	1.86	151.49	0.012	0.015	7.16	0.22	32.82	1.70	1.33	25.9
	20.58	2.58	46.63	0.010	0.002	6.02	0.49	13.63	1.98	1.54	48.06
5	X *	1.51	104.85	0.012	0.011	6.10	0.20	17.53	1.29	1.01	23.5
3	17.55	2.60	149.96	0.012	0.013	7.42	0.27	28.49	1.54	1.20	31.7
1	42.67	0.78	147.83	0.010	0.010	4.84	0.15	34.14	0.69	0.54	14.71
9	40.62	2.03	174.35	0.011	0.012	7.87	0.25	32.54	1.24	0.97	26.98
5	41.74	1.26	221.89	0.012	0.012	5.84	0.20	29.73	1.00	0.78	23.54
5	10.63	2.08	161.24	0.011	0.014	5.94	0.28	27.95	1.16	0.91	30.21
	47.59	9.77	252.37	0.010	0.009	18.90	0.45	42.85	1.86	1.45	44.14
2	22.85	1.37	113.69	0.009	0.012	6.60	0.19	36.17	0.94	0.73	16.77
6	47.50	6.59	191.11	0.008	0.007	19.51	0.30	66.55	1.79	1.40	23.54
0	53.77	1.34	84.73	0.009	0.009	7.57	0.18	44.29	1.16	0.91	15.89
8	17.32	1.00	60.66	0.010	0.012	4.17	0.19	22.42	1.12	0.87	18.64
9	X *	1.60	91.14	0.011	0.010	7.87	0.17	43.97	1.07	0.84	18.34

:d	$\bar{V}_s$ (m/s)	$\bar{V}_{0.6}$ (m/s)	$\bar{\tau}_o$ (kg/m^2)	Fr	Re_{ch}	n	D_{50} (mm)	D_{90} (mm)	g:s	Q (m^3/s)	
	1.69	1.32	48.06	0.71	314286	0.058	26.91	104.68	10.59	7.38	1.47
	1.70	1.33	25.90	0.91	199048	0.038	39.67	97.00	27.48	2.48	
	1.98	1.54	48.06	0.70	513333	0.052	55.71	116.15	111.98	3.97	
	1.29	1.01	23.54	0.72	137415	0.048	35.75	75.58	11.62	1.53	
	1.54	1.20	31.78	0.74	220408	0.050	37.27	103.96	35.91	3.12	
	0.69	0.54	14.71	0.45	55102	0.068	34.29	97.00	6.70	0.42	1.47
	1.24	0.97	26.98	0.62	164966	0.055	69.55	93.05	33.12	1.97	
	1.00	0.78	23.54	0.56	106122	0.062	68.59	97.00	28.69	0.98	
	1.16	0.91	30.21	0.55	173333	0.065	46.85	107.62	29.88	1.89	
	1.86	1.45	44.14	0.69	443878	0.052	37.01	103.96	11.49	14.16	
	0.94	0.73	16.77	0.54	99071	0.055	51.98	101.12	79.63	1.00	1.40
	1.79	1.40	23.54	0.82	300000	0.037	41.64	103.96	22.48	9.23	
	1.16	0.91	15.89	0.69	119562	0.043	20.82	39.67	17.24	1.22	1.37
	1.12	0.87	18.64	0.64	120656	0.048	33.59	86.81	34.90	0.87	
	1.07	0.84	18.34	0.65	104233	0.050	25.99	73.51	8.81	1.34	

n	D_{50} (mm)	D_{90} (mm)	g:s	Q (m^3/s)	ν (m^2/s)	H_2O C°
0.058	26.91	104.68	10.59	7.38	1.47×10^{-6}	6.28
0.038	39.67	97.00	27.48	2.48		
0.052	55.71	116.15	111.98	3.97		
0.048	35.75	75.58	11.62	1.53		
0.050	37.27	103.96	35.91	3.12		
0.068	34.29	97.00	6.70	0.42	1.47×10^{-6}	6.28
0.055	69.55	93.05	33.12	1.97		
0.062	68.59	97.00	28.69	0.98		
0.065	46.85	107.62	29.88	1.89		
0.052	37.01	103.96	11.49	14.16		
0.055	51.98	101.12	79.63	1.00	1.40×10^{-6}	7.50
0.037	41.64	103.96	22.48	9.23		
0.043	20.82	39.67	17.24	1.22	1.37×10^{-6}	8.21
0.048	33.59	86.81	34.90	0.87		
0.050	25.99	73.51	8.81	1.34		

Symbols

tr.	transect
ch.	channel
X	no data
*	subaerial bar in channel
NS	net slope, ie. both + and - gradient along channel length
g:s	gravel to sand ratio

TABLE A

			width (m)			av. depth (m)			width:depth			
tr.	ch.	date	upper	middle	lower	upper	middle	lower	upper	middle	lower	flow area (m^2)
4	4	Aug. 7	5.79	11.89	9.30	0.34	0.20	0.25	17.03	59.45	37.20	2.88
	5	7	4.88	3.05	7.32	0.15	0.23	0.12	32.53	13.26	61.00	0.84
	6	7	5.18	5.79	7.93	0.15	0.12	0.13	34.53	48.25	61.00	0.90
5	1	8	3.66	3.51	6.25	0.10	0.17	0.15	36.60	20.65	41.67	0.60
	2	8	6.10	X	7.01	0.28	X	0.34	21.79	X	20.62	2.17
6	1	9	16.31	X	15.85	0.40	X	0.54	40.78	X	29.35	9.15
	2	9	2.74	5.33	7.01	0.15	0.18	0.12	18.27	29.61	58.42	0.83
	3	9	7.93	X	3.35	0.29	X	0.24	27.35	X	13.96	2.05
	4	9	7.16	X	10.97	0.25	X	0.26	28.64	X	42.19	2.54
7	1	10	7.47	X	5.79	0.11	X	0.12	67.91	X	48.25	0.95
	2	10	5.33	X	5.94	0.16	X	0.16	33.31	X	37.13	0.88
	3	10	7.32	X	6.86	0.19	X	0.18	38.53	X	38.11	1.65
	4	10	6.40	X	8.99	0.23	X	0.17	27.83	X	52.88	1.77
	5	10	17.68	X	20.12	0.36	X	0.37	49.11	X	54.38	8.15
	6	10	13.26	X	13.87	0.46	X	0.38	28.83	X	36.50	6.21

1 of

TABLE A - 2. (continued)

	channel									
lower	flow area (m^2)	length (m)	S_w	S_b	$\bar{w}$	$\bar{d}$	av. w:d	$\bar{V}_s$ (m/s)	$\bar{V}_{0.6}$ (m/s)	$\bar{\tau}_o$ (kg/m^2
37.20	2.88	137.77	0.007	0.006	8.99	0.26	37.89	1.45	1.13	17.85
61.00	0.84	36.27	0.011	0.012	5.08	0.17	35.60	1.27	0.99	18.34
61.00	0.90	48.77	0.016	0.015	6.30	0.13	47.93	0.64	0.50	20.40
41.67	0.60	212.45	0.007	0.008	4.47	0.14	32.97	0.71	0.55	9.61
20.62	2.17	56.08	0.009	0.010	6.56	0.31	21.21	1.62	1.26	27.36
29.35	9.15	40.84	0 NS	0.009	16.08	0.47	35.07	1.19	0.93	41.49
58.42	0.83	95.40	0.004	0.006	5.03	0.15	35.43	0.62	0.48	5.89
13.96	2.05	62.18	0.005	0.003	5.64	0.27	20.66	1.01	0.79	13.24
42.19	2.54	32.31	0.003	0.002	9.07	0.26	35.42	0.90	0.70	7.50
48.25	0.95	39.32	0.006	0.010	6.63	0.12	58.08	0.77	0.60	6.77
37.13	0.88	28.04	0.005	0.009	5.64	0.16	35.22	0.85	0.66	7.85
38.11	1.65	26.52	0.003	0.010	7.09	0.19	38.32	0.88	0.69	5.44
52.88	1.77	29.57	0.004	0.001	7.70	0.20	40.36	0.99	0.77	7.85
54.38	8.15	26.82	0.003	0.002	18.90	0.37	51.75	0.71	0.55	10.74
36.50	6.21	34.75	0.002	+ 0.010	13.57	0.42	32.67	1.16	0.91	8.24

2of

$_o$ (kg/m^2)	Fr	Re$_{ch}$	n	D$_{50}$ (mm)	D$_{90}$ (mm)	g:s	Q (m^3/s)	ν (m^2/s)	H_2O C°
85	0.71	214453	0.038	32.00	103.24	8.76	3.25	1.37 x 10^{-6}	8.21
34	0.77	122847	0.042	19.29	36.76	8.71	0.83		
40	0.44	47445	0.084	36.76	61.81	8.86	0.45		
61	0.47	56204	0.053	34.29	56.10	9.09	0.33	1.37 x 10^{-6}	8.45
36	0.72	285110	0.045	20.97	47.83	6.89	2.73		
49	0.43	323778	0.080	13.00	36.00	3.86	8.51	1.35 x 10^{-6}	8.88
9	0.40	53333	0.048	17.75	39.67	7.32	0.40		
24	0.49	158000	0.048	16.00	63.99	5.66	1.62		
0	0.44	132222	0.042	17.15	30.06	6.22	1.78		
7	0.57	51880	0.040	19.03	37.53	6.95	0.57	1.33 x 10^{-6}	9.52
5	0.53	79399	0.040	12.73	22.78	7.19	0.58		
4	0.51	95977	0.033	8.28	18.64	3.25	1.14		
5	0.55	115790	0.037	8.57	24.08	3.24	1.36		
74	0.29	150940	0.067	10.93	40.78	3.96	4.48		
4	0.45	287368	0.037	13.93	29.86	11.35	5.65		

tr/ch	a	B^*	d_c^*	R	$\tilde{Q}$	Q (m^3/s)	V_{st} (m/s)	λ
1/1	37.39	498.52	13.33	1.7	22522.03	11.02	2.52	0.67
1/2	29.83	179.0	6.0		1896.33	2.48	1.70	1.0
1/3	12.29	107.50	8.75		1746.73	5.29	2.65	0.75
1/4	26.52	169.44	6.39		1977.74	1.99	1.68	0.77
1/5	23.94	200.54	8.38		3674.50	3.95	1.94	0.79
2/1	32.27	142.35	4.41	1.7	820.65	0.71	1.16	0.59
2/2	29.15	112.43	3.86		537.74	2.85	1.80	0.69
2/3	26.55	84.64	3.19		303.30	1.55	1.58	0.63
2/4	18.00	126.38	7.02		1585.12	3.10	1.89	0.61
2/5	40.21	510.81	12.70		18042.74	19.40	2.56	0.73
3/1	33.00	126.92	3.85	1.7	551.96	1.39	1.31	0.72
3/2	62.94	464.52	7.38		5955.73	8.79	1.71	1.05
4/1	42.10	360.48	8.57	1.7	6205.69	1.62	1.55	0.75
4/2	18.96	122.65	6.47		1285.93	1.12	1.43	0.78
4/3	43.72	302.69	6.92		4013.23	1.79	1.43	0.75
4/4	32.11	280.94	8.75		4341.84	3.25	1.45	1.0
4/5	29.88	267.37	8.95		5352.77	1.09	1.67	0.76
4/6	45.00	170.27	3.78		975.48	1.05	1.48	0.43
5/1	31.93	131.47	4.12	1.7	564.44	0.49	1.06	0.67
5/2	19.88	312.38	15.71		14125.00	3.69	2.18	0.74
6/1	31.53	1236.92	39.23	1.7	277404.91	21.83	3.04	0.39
6/2	31.44	279.44	8.89		3348.55	0.59	0.91	0.68
6/3	18.19	352.50	19.38		16776.52	2.22	1.39	0.73

Table A-3. The values of some of the parameters required for the calculation and the correction of the discharge values of the theoretical discharge data set (refer to equations 3.2 - 3.5 inclusive). The remaining parameters required for the calculations and the corrected discharge values are presented in table A-2. Continued on the next page.

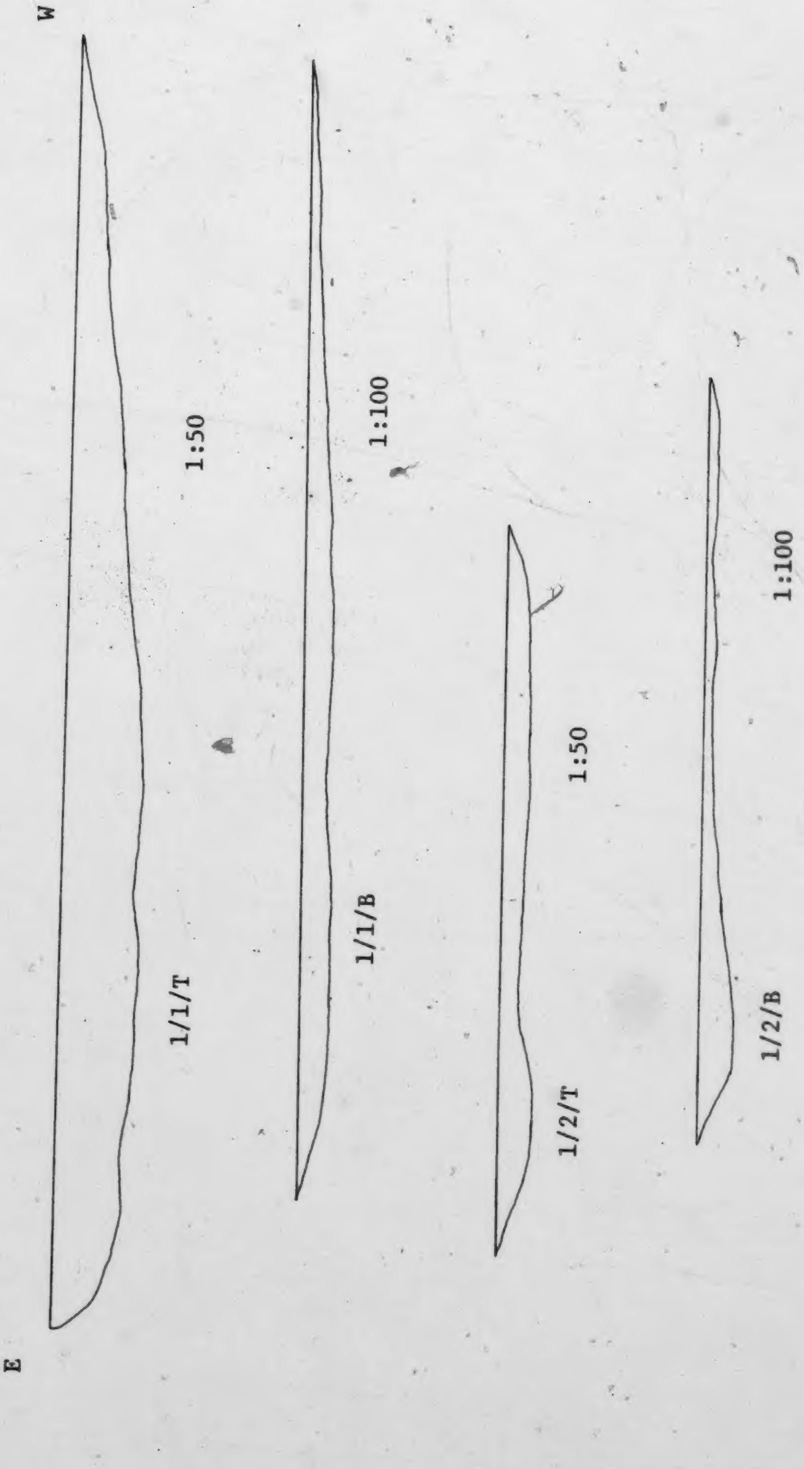
tr/ch	a	B^*	d_c^*	R	$\tilde{Q}$	Q (m^3/s)	V_{st} (m/s)	λ
6/4	32.98	533.53	16.18		15379.19	2.37	1.20	0.75
7/1	51.00	348.95	6.84	1.7	3375.77	0.69	0.93	0.83
7/2	35.25	433.85	12.31		10191.48	0.80	1.18	0.72
7/3	33.76	886.25	26.25		58252.49	1.36	1.05	0.84
7/4	36.67	855.56	23.33		53437.25	1.68	1.22	0.81
7/5	51.08	1718.18	33.64		176300.91	9.14	1.45	0.49
7/6	30.84	969.29	31.43		70180.15	6.65	1.37	0.85

Table A-3. Continued.

Appendix B - Flow Cross Sections Of The Theoretical Discharge Data Set

Each of the following flow cross sections has an identifying number and scale presented with it. The cross section was identified by the number of its transect (see figure 1-3), the number given to its channel on that transect and by the position of the cross section along the channel length (upper, middle or lower). For example, the upper flow cross section of channel number two on transect number one would be given the identifying number 1/2/T. The following two points should be kept in mind when examining the flow cross sections:

1. All the flow cross sections were drawn with the assumption of a horizontal water surface.
2. The flow cross sections were constructed with the perspective of looking south from highway 93.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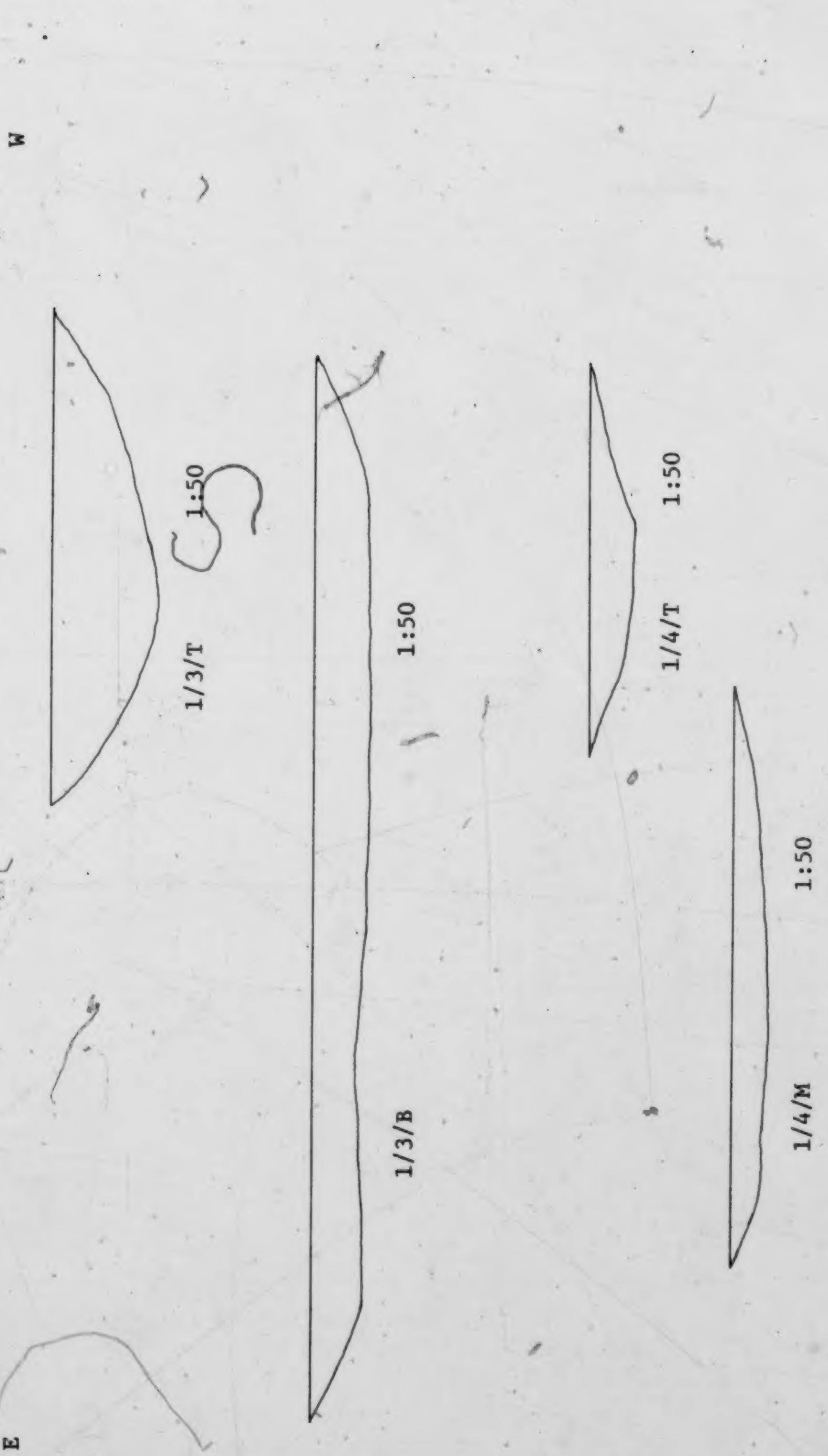
1/2/T
1:100
1/2/B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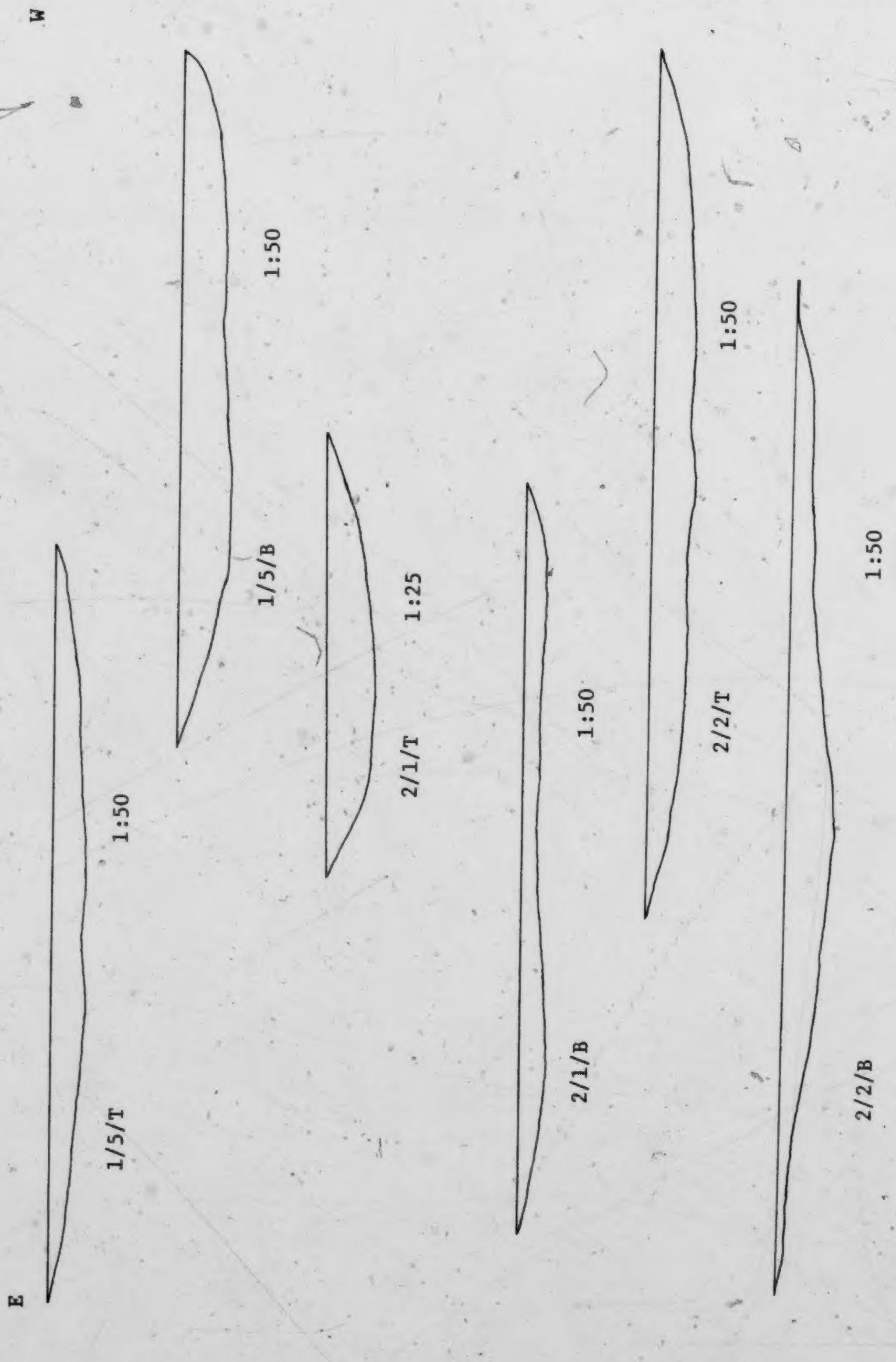
1/4/M
1:50
E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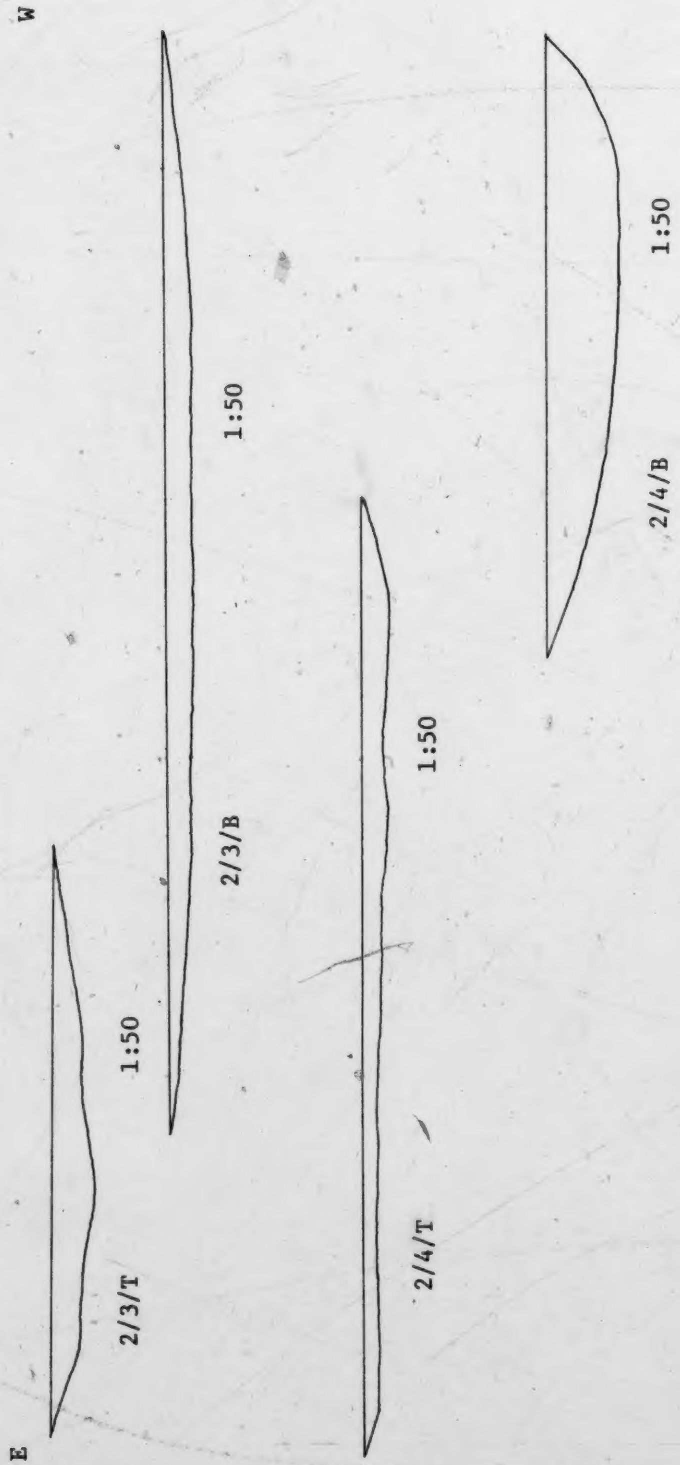
2/2/B
1:50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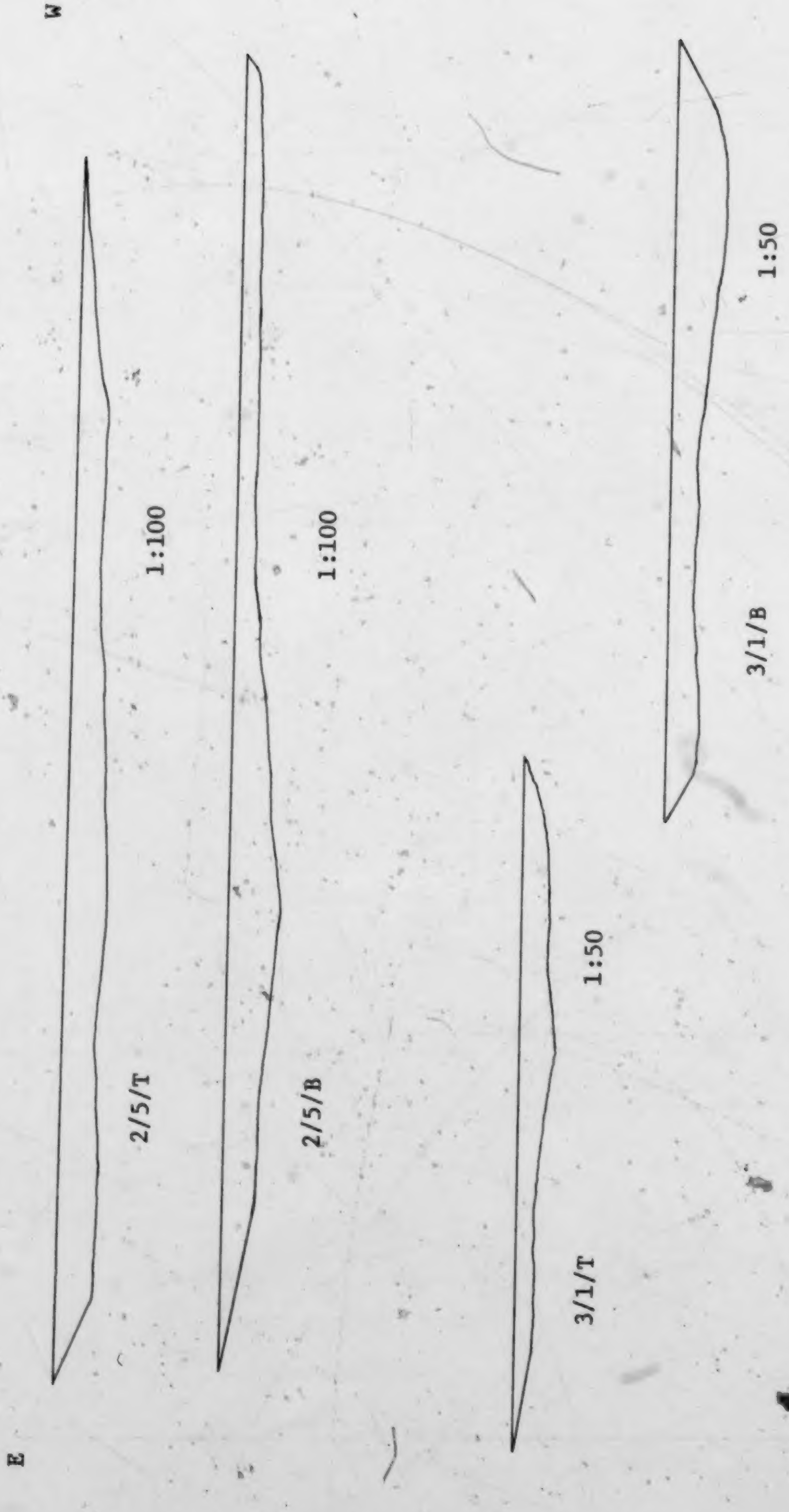
2/4/B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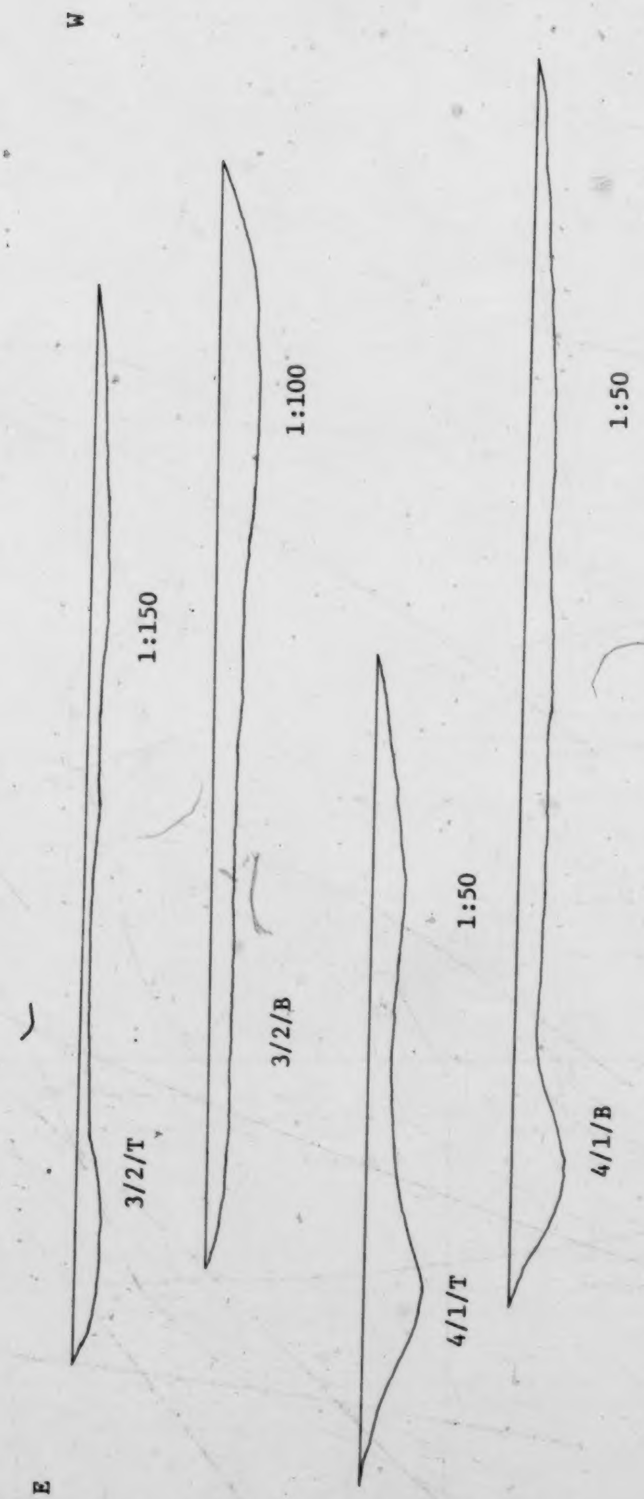
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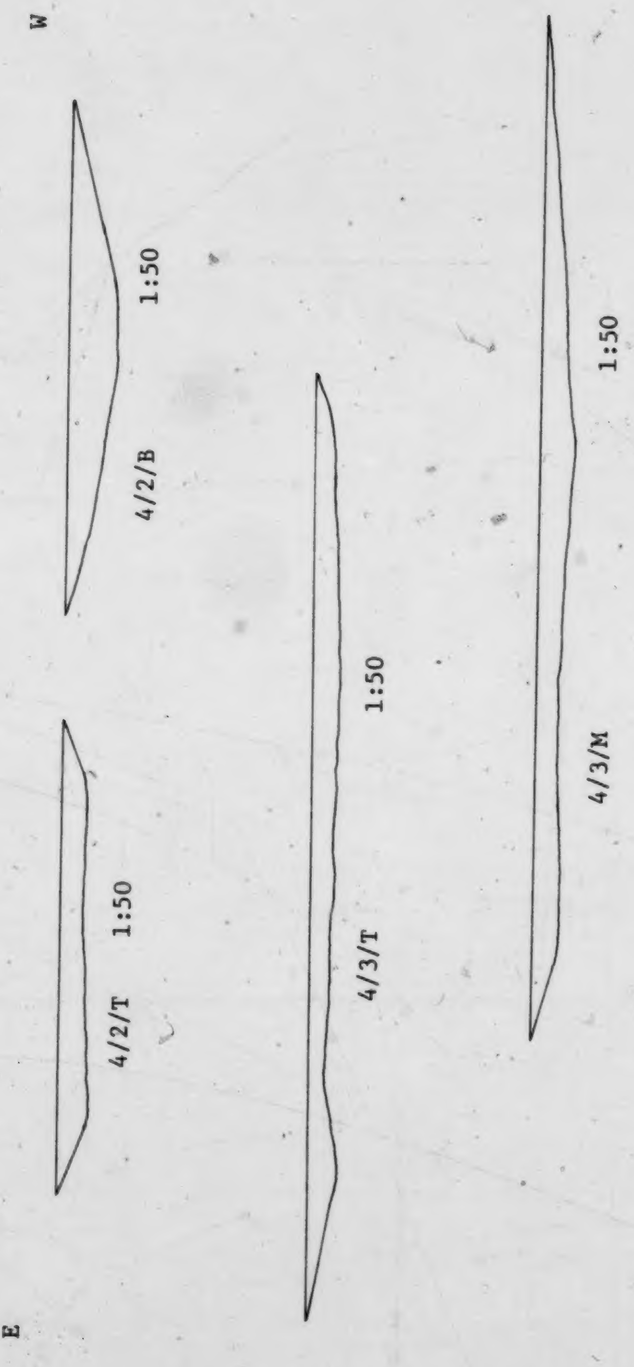
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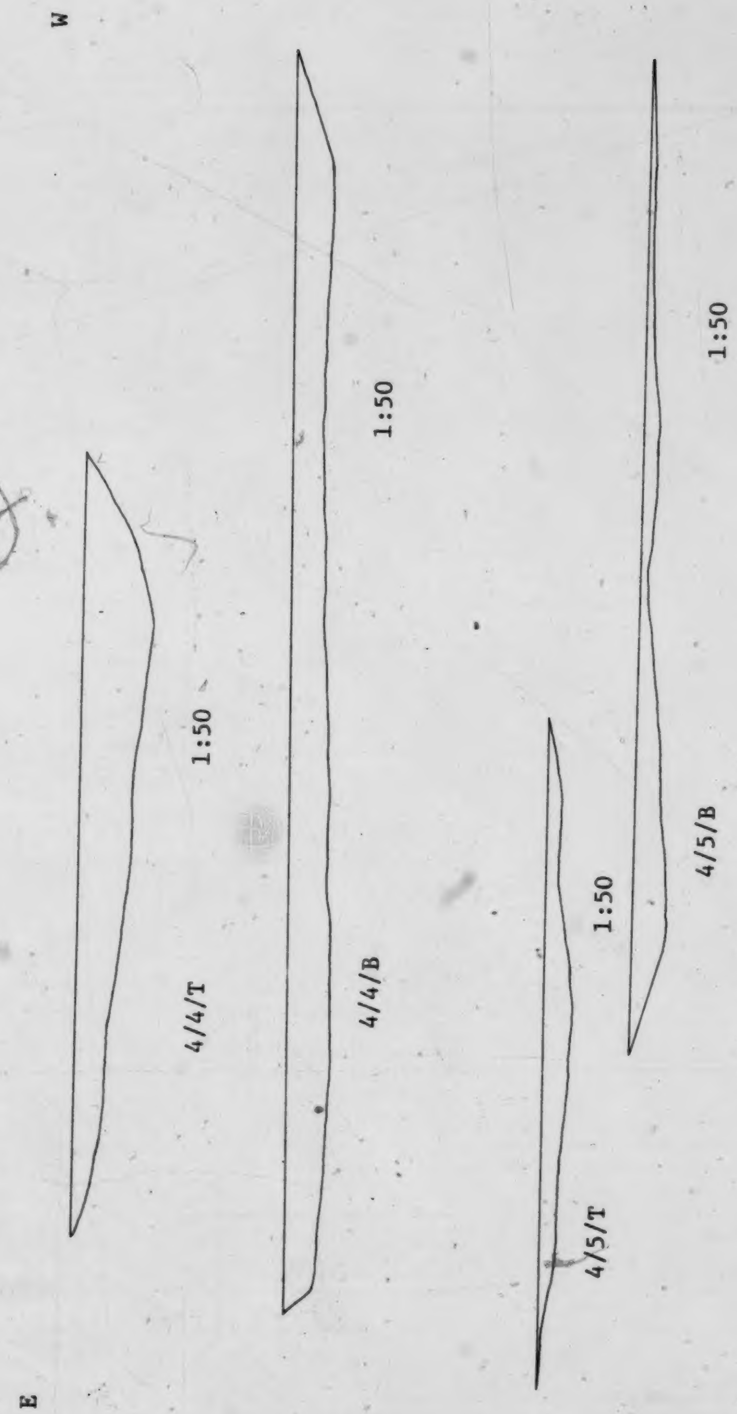
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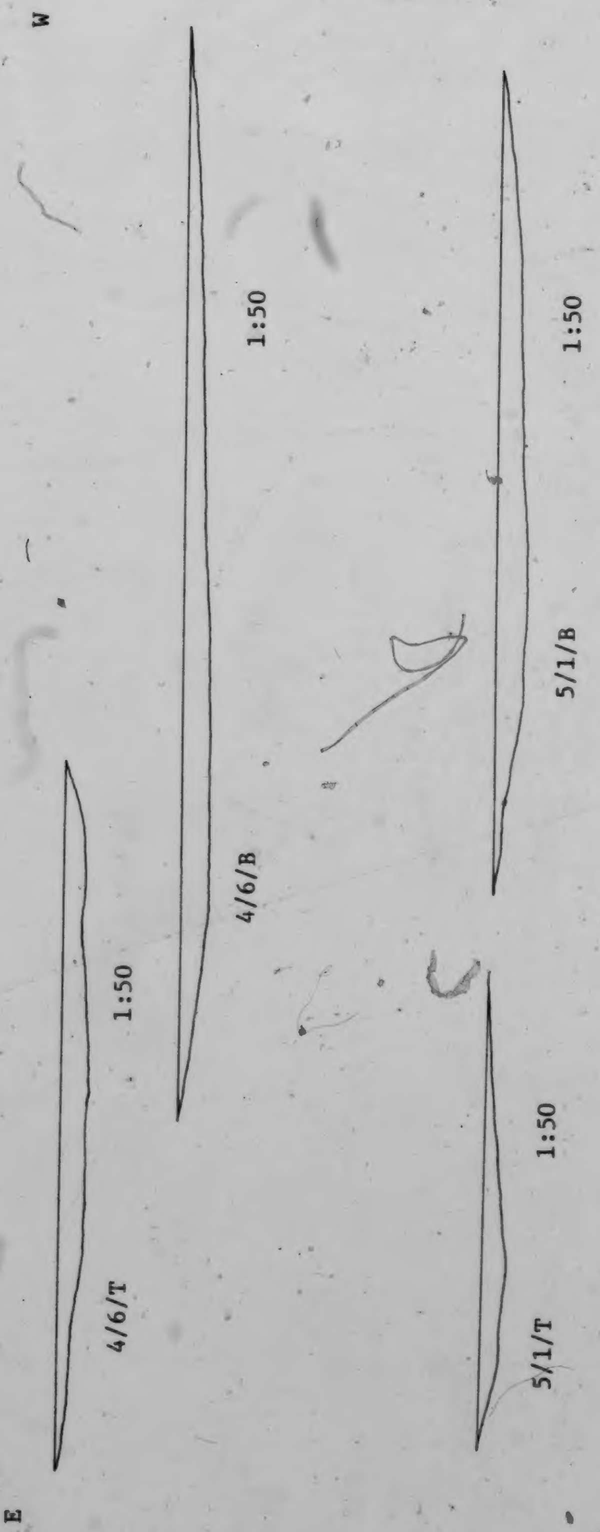
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4/6/T
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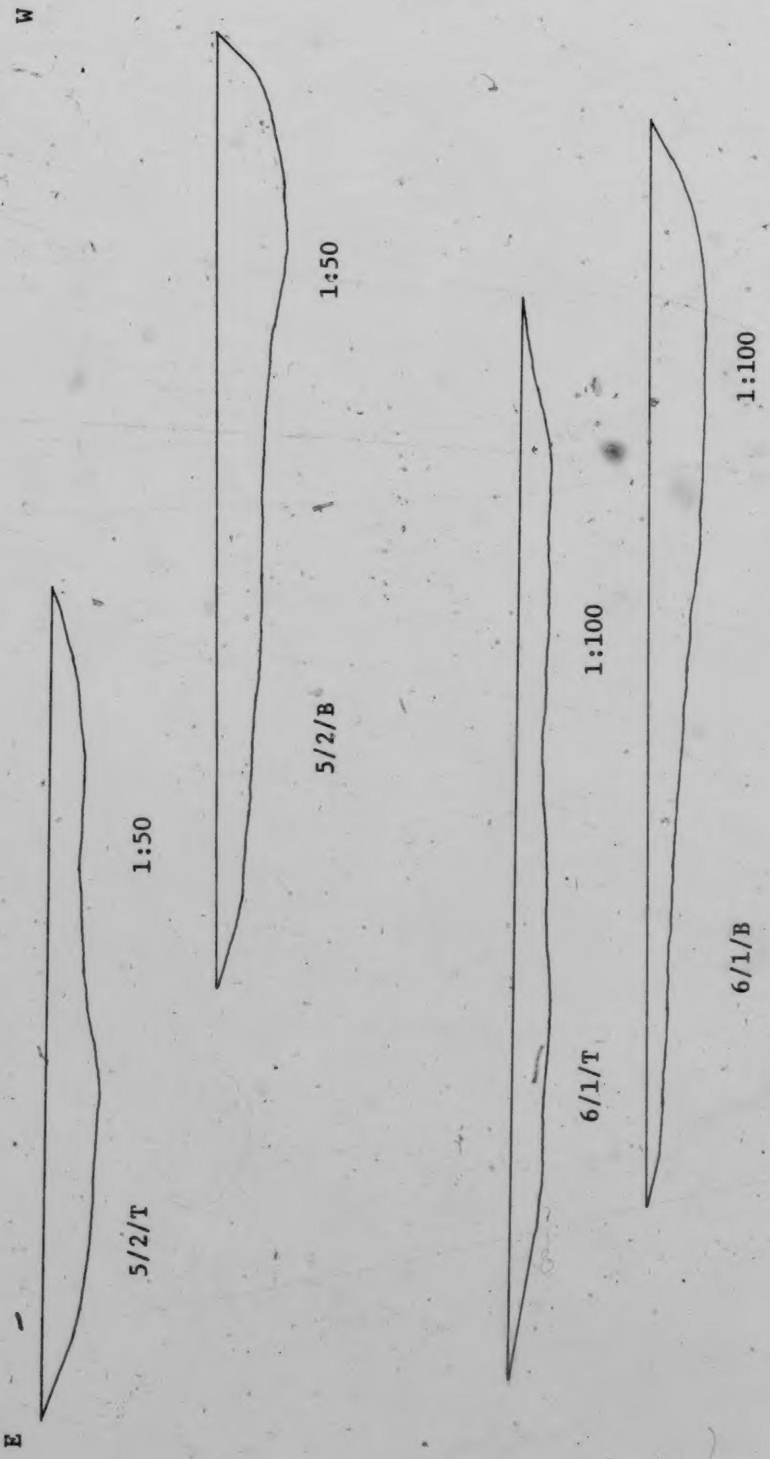
5/1/T
E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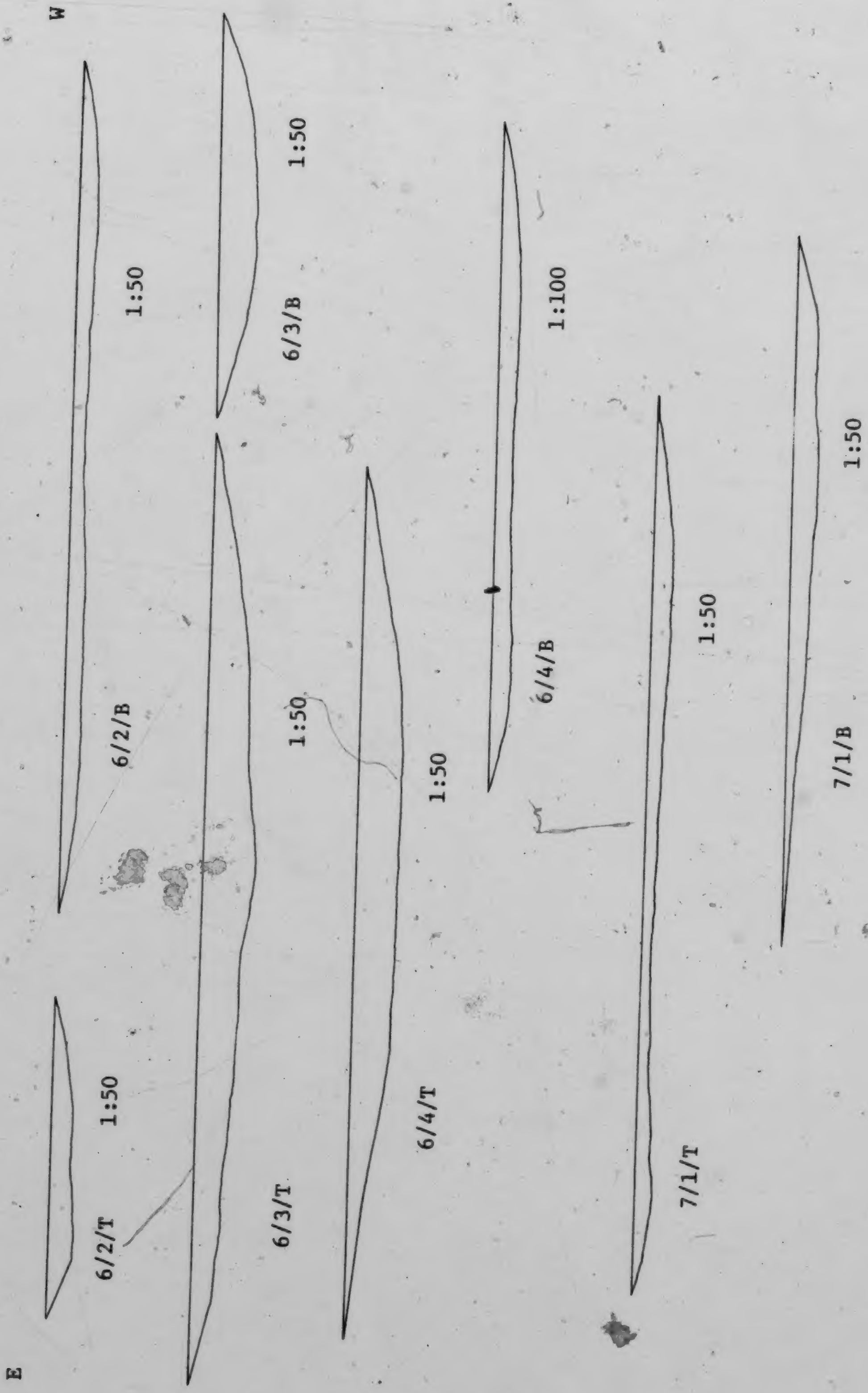
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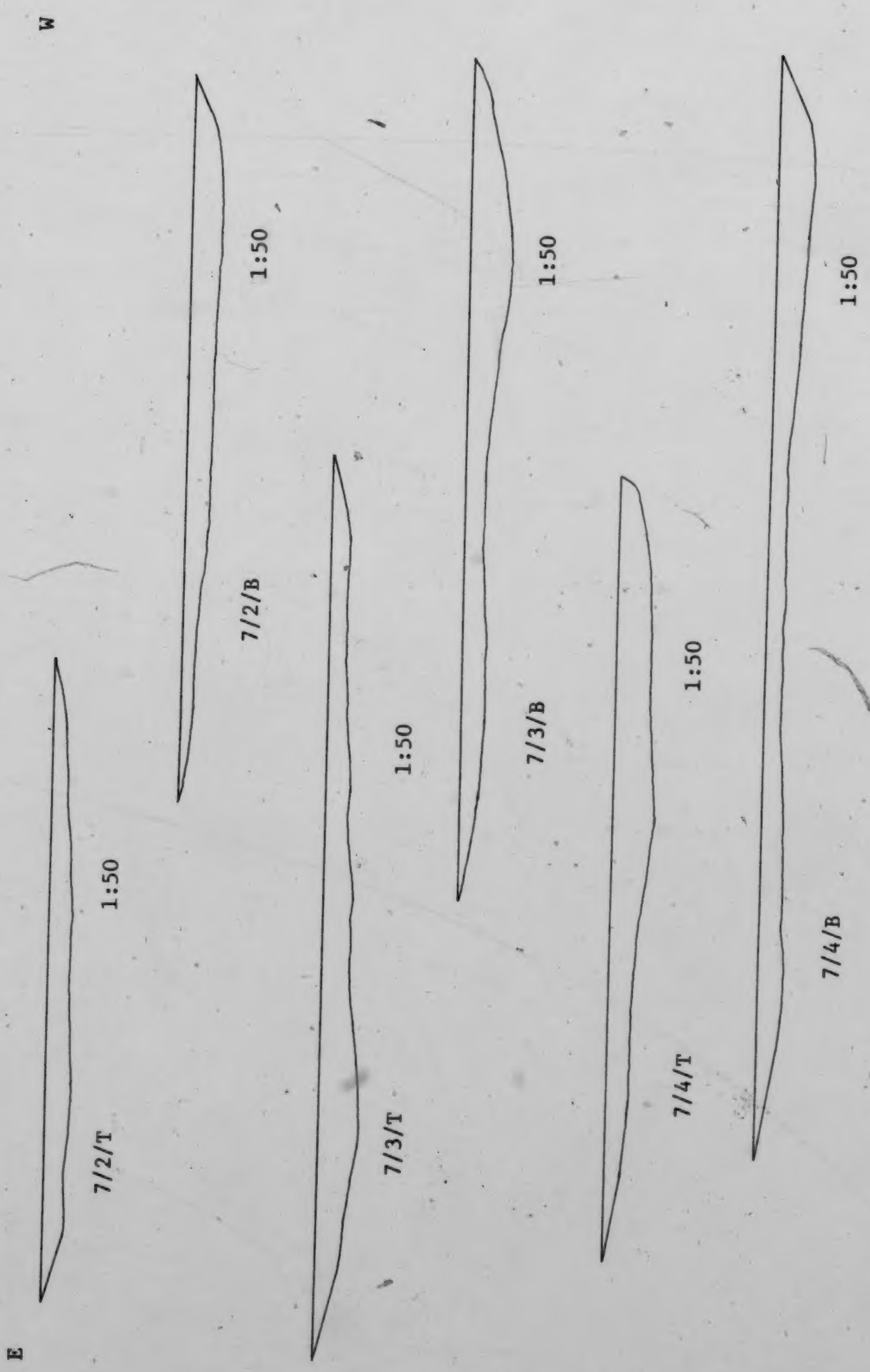
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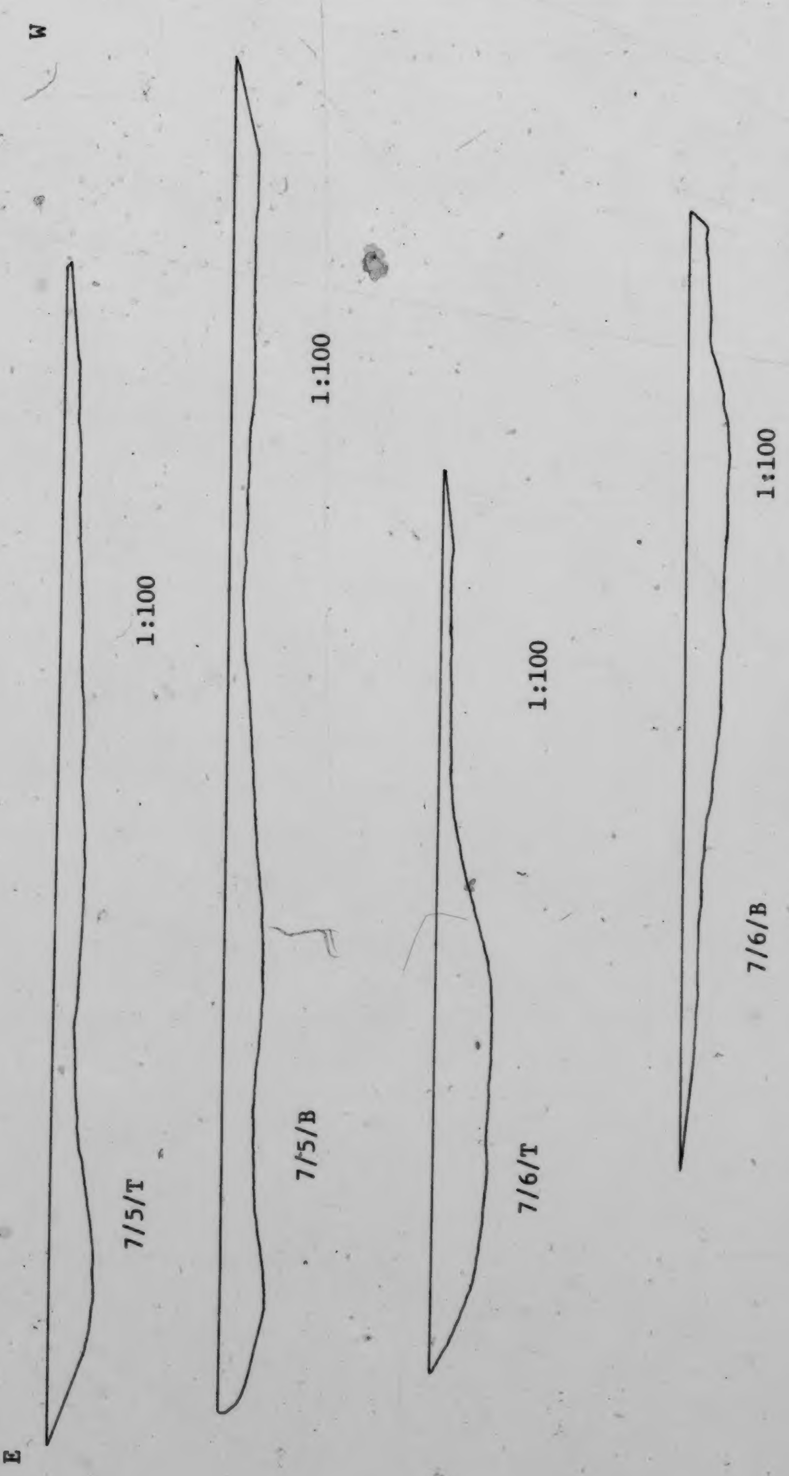
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E
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7/5/T
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7/5/B
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7/6/T
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7/6/B

Appendix C - Grain Size Data Of The Channel Grab Samples

	channel 1/1		channel 1/2		channel 1/3	
sieve size	weight retained (gm)	cumulative % finer	weight retained (gm)	cumulative % finer	weight retained (gm)	cumulative % finer
3.0 "	0	100.0	0	100.0	2598.0	58.03
2.5 "	1653.0	70.27	1030.3	73.29	0	58.03
2.0 "	0	70.27	306.5	65.34	611.1	48.16
1 7/8 "	0	70.27	0	65.34	0	48.16
1 3/4 "	190.9	66.84	506.0	52.23	224.5	44.53
1.5 "	157.7	64.0	178.4	47.60	282.0	39.98
1.0 "	985.1	46.28	403.7	37.14	1210.0	20.43
7/8 "	373.6	39.56	153.2	33.16	239.2	16.57
3/4 "	173.1	36.45	162.4	28.95	126.7	14.52
5/8 "	288.1	31.27	152.9	24.99	210.6	11.12
1/2 "	221.1	27.29	130.5	21.61	200.1	7.89
3/8 "	283.7	22.19	220.7	15.88	146.3	5.52
1/4 "	272.2	17.29	215.6	10.30	114.4	3.67
# 4	145.5	14.67	101.4	7.67	65.5	2.62
# 5	83.7	13.17	48.7	6.40	32.9	2.08
# 8	184.6	9.85	94.2	3.96	61.0	1.10
# 10	67.0	8.64	19.0	3.47	14.3	0.87
# 14	23.2	6.73	37.9	2.49	17.3	0.59
# 18	24.1	4.75	29.5	1.72	10.3	0.42
# 25	23.1	2.84	24.2	1.09	8.3	0.29
# 35	18.7	1.30	16.5	0.67	8.1	0.16
# 45	10.0	0.48	8.6	0.44	5.8	0.06
# 60	3.7	0.17	5.8	0.29	2.5	0.02
# 80	1.1	0.08	4.7	0.17	0.7	0.01
# 120	0.6	0.03	3.6	0.08	0.3	0.006
# 170	0.2	0.02	2.0	0.03	0.2	0.003
# 230	0.2	0	1.0	0	0.2	0

sieve size	channel 1/4		channel 1/5		channel 2/1	
	weight retained (gm)	cumulative % finer	weight retained (gm)	cumulative % finer	weight retained (gm)	cumulative % finer
3.0 "	422.2	93.93	1138.2	78.96	1287.0	83.14
2.5 "	1241.0	76.08	630.3	67.31	861.9	71.85
2.0 "	230.4	72.77	239.9	62.88	243.9	68.65
1 7/8 "	443.5	66.39	0	62.88	277.2	65.02
1 3/4 "	587.2	57.94	377.7	55.89	437.8	59.28
1.5 "	182.6	55.32	229.2	51.66	195.0	56.73
1.0 "	1151.0	38.76	869.9	35.58	949.7	44.29
7/8 "	298.2	34.47	218.4	31.54	184.4	41.87
3/4 "	218.6	31.33	140.1	28.95	177.5	39.54
5/8 "	271.5	27.43	308.0	23.26	359.2	34.84
1/2 "	248.5	23.85	258.5	18.48	250.3	31.56
3/8 "	313.6	19.34	188.1	15.0	370.4	26.71
1/4 "	293.5	15.12	215.6	11.02	378.2	21.75
# 4	164.5	12.75	106.8	9.04	217.6	18.90
# 5	93.6	11.41	59.1	7.95	106.3	17.51
# 8	190.7	8.67	112.5	5.87	252.2	14.20
# 10	62.2	7.77	32.1	5.28	98.7	12.91
# 14	22.9	6.44	34.4	4.0	17.2	11.10
# 18	24.0	5.04	29.4	2.92	20.6	8.93
# 25	26.7	3.48	25.9	1.96	22.1	6.61
# 35	25.4	2.0	22.8	1.12	22.3	4.26
# 45	17.3	1.0	16.9	0.49	17.7	2.40
# 60	9.2	0.46	8.8	0.17	11.7	1.17
# 80	4.1	0.22	2.8	0.06	6.0	0.54
# 120	2.2	0.09	1.0	0.03	3.0	0.22
# 170	1.0	0.04	0.5	0.01	1.4	0.07
# 230	0.6	0	0.2	0	0.7	0

sieve size	channel 2/2		channel 2/3		channel 2/4	
	weight retained (gm)	cumulative % finer	weight retained (gm)	cumulative % finer	weight retained (gm)	cumulative % finer
3.0 "	1560.0	77.05	2071.0	67.2	0	100
2.5 "	2344.3	42.56	1065.0	50.33	2018.3	68.17
2.0 "	362.9	37.22	0	50.33	435.3	61.31
1 7/8 "	0	37.22	0	50.33	239.9	57.52
1 3/4 "	311.5	32.64	718.2	38.95	1082.3	40.46
1.5 "	410.6	26.60	181.0	36.09	99.1	38.89
1.0 "	565.6	18.28	763.7	23.99	906.1	24.61
7/8 "	58.2	17.42	77.6	22.76	246.1	20.72
3/4 "	173.1	14.88	196.0	19.66	149.7	18.36
5/8 "	204.7	11.87	187.0	16.70	209.7	15.06
1/2 "	122.2	10.07	198.4	13.55	205.4	11.82
3/8 "	122.5	8.27	195.3	10.46	141.6	9.58
1/4 "	145.7	6.12	191.0	7.44	151.2	7.20
# 4	78.9	4.96	81.5	6.14	70.1	6.09
# 5	33.0	4.48	52.1	5.32	47.2	5.35
# 8	83.8	3.24	98.6	3.76	105.1	3.69
# 10	23.2	2.90	26.0	3.35	33.6	3.16
# 14	24.2	2.17	27.2	2.5	28.4	2.28
# 18	22.1	1.51	21.4	1.83	20.7	1.64
# 25	19.3	0.92	19.1	1.23	14.8	1.18
# 35	14.5	0.49	15.5	0.75	11.1	0.83
# 45	8.7	0.22	11.2	0.40	8.6	0.57
# 60	4.3	0.09	6.5	0.20	7.8	0.32
# 80	1.7	0.04	3.3	0.09	5.4	0.16
# 120	0.9	0.02	1.8	0.04	3.0	0.06
# 170	0.3	0.01	0.7	0.02	1.3	0.02
# 230	0.2	0	0.5	0	0.7	0

sieve size	channel 2/5		channel 3/1		channel 3/2	
	weight retained (gm)	cumulative % finer	weight retained (gm)	cumulative % finer	weight retained (gm)	cumulative % finer
3.0 "	931.2	79.15	1454.0	77.74	0	100
2.5 "	393.7	70.34	0	77.74	2050.0	68.09
2.0 "	173.1	66.46	1820.3	49.86	321.5	63.09
1 7/8 "	0	66.46	0	49.86	0	63.09
1 3/4 "	180.3	62.43	160.9	47.4	769.6	51.11
1.5 "	459.3	52.15	318.2	42.53	273.5	46.85
1.0 "	587.5	38.99	1263.0	23.19	836.7	33.83
7/8 "	159.9	35.41	174.7	20.51	147.1	31.54
3/4 "	221.1	30.46	297.0	15.97	236.6	27.86
5/8 "	126.7	27.63	193.4	13.01	337.2	22.61
1/2 "	179.0	23.62	248.1	9.21	267.2	18.45
3/8 "	165.1	19.92	172.1	6.57	237.5	14.76
1/4 "	180.5	15.88	175.3	3.89	245.6	10.93
# 4	123.4	13.12	67.1	2.86	140.1	8.75
# 5	46.5	12.08	34.0	2.34	76.2	7.57
# 8	142.6	8.89	57.4	1.46	174.9	4.84
# 10	44.1	7.90	14.9	1.23	39.1	4.24
# 14	16.9	6.32	21.3	0.91	40.5	3.02
# 18	14.3	4.98	15.4	0.67	30.7	2.10
# 25	14.3	3.64	13.9	0.46	26.8	1.29
# 35	14.5	2.28	12.5	0.27	21.5	0.65
# 45	12.0	1.16	8.5	0.14	12.8	0.26
# 60	7.7	0.44	4.8	0.06	5.5	0.10
# 80	3.0	0.16	2.2	0.03	1.9	0.04
# 120	1.1	0.06	1.1	0.01	0.9	0.01
# 170	0.3	0.03	0.4	0.005	0.2	0.01
# 230	0.3	0	0.3	0	0.2	0

sieve size	channel 4/1 weight retained (gm)	channel 4/1 cumulative % finer	channel 4/2 weight retained (gm)	channel 4/2 cumulative % finer	channel 4/3 weight retained (gm)	channel 4/3 cumulative % finer
3.0 "	0	100	0	100	0	100
2.5 "	0	100	1087.2	82.36	462.8	88.69
2.0 "	296.9	94.5	294.7	77.58	0	88.69
1 7/8 "	0	94.5	467.9	69.98	0	88.69
1 3/4 "	182.2	91.13	467.2	62.40	438.0	77.98
1.5 "	555.6	80.84	345.4	56.80	179.7	73.59
1.0 "	1320.0	56.39	1156.0	38.04	927.9	50.91
7/8 "	231.7	52.10	231.1	34.29	92.6	48.62
3/4 "	193.1	48.52	291.0	29.57	131.1	45.44
5/8 "	350.2	42.04	370.1	23.56	225.9	39.92
1/2 "	318.9	36.13	335.1	18.13	247.9	33.86
3/8 "	370.6	29.27	255.8	13.98	233.2	28.15
1/4 "	388.7	22.07	305.1	9.03	254.7	21.93
# 4	279.6	16.89	123.7	7.02	135.9	18.61
# 5	207.4	13.05	82.5	5.68	63.0	17.07
# 8	356.4	6.45	147.7	3.28	222.5	11.63
# 10	71.7	5.12	32.1	2.76	64.3	10.06
# 14	31.1	3.94	57.4	1.83	23.6	7.8
# 18	9.5	3.58	36.9	1.23	19.1	5.97
# 25	3.9	3.43	27.9	0.78	16.5	4.40
# 35	3.4	3.30	21.3	0.43	14.7	2.99
# 45	6.4	3.05	11.3	0.25	11.5	1.89
# 60	17.0	2.40	5.8	0.16	8.2	1.11
# 80	24.4	1.47	4.2	0.09	5.4	0.59
# 120	20.8	0.68	3.0	0.04	3.5	0.26
# 170	12.0	0.22	1.6	0.01	1.8	0.09
# 230	5.8	0	0.8	0	0.9	0

sieve size	channel 4/4		channel 4/5		channel 4/6	
	weight retained (gm)	cumulative % finer	weight retained (gm)	cumulative % finer	weight retained (gm)	cumulative % finer
3.0 "	0	100	0	100	0	100
2.5 "	1694.0	72.05	0	100	379.6	92.42
2.0 "	467.2	64.34	0	100	1189.3	68.67
1 7/8 "	0	64.34	0	100	0	68.67
1 3/4 "	0	64.34	213.7	95.51	258.4	63.50
1.5 "	477.5	56.45	229.9	90.67	547.0	52.58
1.0 "	620.7	46.21	1179.0	65.87	434.0	43.91
7/8 "	183.6	43.18	266.4	60.27	178.2	40.35
3/4 "	258.6	38.91	438.5	51.04	143.1	37.49
5/8 "	328.3	33.50	296.1	44.81	269.8	32.11
1/2 "	290.1	28.71	338.9	37.69	172.4	28.66
3/8 "	289.4	23.93	372.5	29.85	209.0	24.49
1/4 "	323.2	18.60	399.6	21.44	203.7	20.42
# 4	156.1	16.02	197.8	17.28	148.4	17.46
# 5	96.2	14.44	74.7	15.71	83.5	15.79
# 8	197.4	11.18	207.1	11.36	213.0	11.53
# 10	60.7	10.18	63.3	10.03	71.9	10.1
# 14	27.3	8.45	25.1	7.97	27.6	7.84
# 18	27.9	6.69	24.3	5.97	22.7	5.98
# 25	29.2	4.84	22.3	4.14	18.9	4.43
# 35	30.7	2.90	18.7	2.61	19.8	2.81
# 45	25.5	1.29	13.7	1.49	18.1	1.33
# 60	13.1	0.46	9.0	0.75	9.7	0.53
# 80	4.4	0.18	4.7	0.36	3.5	0.25
# 120	1.8	0.07	2.6	0.15	1.7	0.11
# 170	0.7	0.03	1.0	0.07	0.8	0.04
# 230	0.4	0	0.8	0	0.5	0

sieve size	channel 5/1		channel 5/2		channel 6/1	
	weight retained (gm)	cumulative % finer	weight retained (gm)	cumulative % finer	weight retained (gm)	cumulative % finer
3.0 "	0	100	0	100	0	100
2.5 "	370.1	94.90	0	100	0	100
2.0 "	840.5	83.31	228.5	96.28	0	100
1 7/8 "	547.9	75.76	172.6	93.47	0	100
1 3/4 "	596.2	67.54	551.4	84.50	263.6	95.12
1.5 "	788.7	56.66	364.0	78.58	91.3	93.43
1.0 "	1141.0	40.93	1419.0	55.49	873.8	77.25
7/8 "	290.2	36.93	308.9	50.47	415.8	69.55
3/4 "	200.2	34.17	207.9	47.08	393.2	62.27
5/8 "	290.6	30.16	320.4	41.87	324.8	56.26
1/2 "	266.8	26.48	323.5	36.61	388.7	49.06
3/8 "	285.8	22.54	358.2	30.78	402.6	41.60
1/4 "	336.8	17.90	363.3	24.87	410.6	34.0
# 4	189.5	15.29	228.0	21.16	257.1	29.24
# 5	119.5	13.64	135.8	18.95	124.8	26.93
# 8	215.9	10.66	301.4	14.05	276.9	21.80
# 10	61.0	9.82	93.2	12.53	65.6	20.59
# 14	28.8	8.14	26.2	9.24	17.8	17.83
# 18	28.7	6.46	22.6	6.41	17.0	15.20
# 25	30.1	4.70	18.6	4.07	21.5	11.87
# 35	29.3	2.99	13.1	2.43	29.7	7.28
# 45	20.8	1.77	8.2	1.40	26.9	3.11
# 60	11.6	1.09	5.1	0.76	13.2	1.07
# 80	6.8	0.70	2.9	0.40	3.9	0.46
# 120	5.6	0.37	1.9	0.16	1.5	0.23
# 170	4.0	0.13	0.9	0.05	0.8	0.11
# 230	2.3	0	0.37	0	0.7	0

sieve size	channel 6/2 weight retained (gm)	channel 6/2 cumulative % finer	channel 6/3 weight retained (gm)	channel 6/3 cumulative % finer	channel 6/4 weight retained (gm)	channel 6/4 cumulative % finer
3.0 "	0	100	0	100	0	100
2.5 "	0	100	633.3	89.36	0	100
2.0 "	0	100	0	89.36	0	100
1 7/8 "	293.7	94.99	0	89.36	0	100
1 3/4 "	0	94.99	109.2	87.52	0	100
1.5 "	486.0	86.70	153.3	84.94	0	100
1.0 "	1107.3	67.82	1312.0	62.89	2064.5	62.06
7/8 "	304.4	62.63	201.9	59.50	229.1	57.85
3/4 "	457.4	54.83	281.2	54.77	236.9	53.50
5/8 "	462.3	46.94	341.0	49.04	413.1	45.91
1/2 "	433.6	39.55	433.9	41.75	317.4	40.08
3/8 "	449.5	31.88	395.3	35.10	427.6	32.22
1/4 "	480.2	23.69	467.3	27.25	334.9	26.07
# 4	250.3	19.42	274.1	22.64	199.8	22.39
# 5	127.3	17.25	119.6	20.63	83.3	20.86
# 8	259.5	12.83	274.9	16.01	205.7	17.08
# 10	66.8	11.69	80.7	14.65	61.8	15.95
# 14	11.8	10.11	15.2	12.33	17.1	13.50
# 18	10.0	8.77	12.6	10.41	14.2	11.47
# 25	10.1	7.42	14.2	8.24	14.4	9.41
# 35	11.3	5.90	16.7	5.69	17.2	6.94
# 45	11.8	4.33	15.4	3.34	19.0	4.22
# 60	13.1	2.57	11.7	1.56	14.3	2.18
# 80	8.8	1.39	5.4	0.73	7.2	1.15
# 120	5.7	0.63	2.8	0.31	4.3	0.53
# 170	3.1	0.21	1.3	0.11	2.4	0.19
# 230	1.6	0	0.7	0	1.3	0

sieve size	channel 7/1		channel 7/2		channel 7/3	
	weight retained (gm)	cumulative % finer	weight retained (gm)	cumulative % finer	weight retained (gm)	cumulative % finer
3.0 "	0	100	0	100	0	100
2.5 "	0	100	0	100	0	100
2.0 "	0	100	0	100	0	100
1 7/8 "	0	100	0	100	0	100
1 3/4 "	342.0	93.98	0	100	0	100
1.5 "	0	93.98	0	100	0	100
1.0 "	1767.0	62.84	488.6	91.69	31.3	99.38
7/8 "	292.7	57.69	357.5	85.60	218.7	95.02
3/4 "	332.7	51.83	497.3	77.14	121.8	92.59
5/8 "	360.6	45.47	825.8	63.09	579.4	81.05
1/2 "	265.9	40.79	761.2	50.14	587.9	69.33
3/8 "	344.5	34.72	687.2	38.45	716.4	55.06
1/4 "	409.3	27.51	601.5	28.22	656.9	41.97
# 4	277.0	22.63	376.2	21.82	370.1	34.60
# 5	148.7	20.01	165.4	19.00	164.2	31.32
# 8	336.7	14.08	324.6	13.48	319.1	24.97
# 10	89.3	12.50	88.6	11.97	77.8	23.42
# 14	20.1	9.56	15.6	9.79	14.1	20.96
# 18	15.7	7.27	15.2	7.67	13.5	18.60
# 25	11.0	5.66	17.3	5.26	18.3	15.41
# 35	7.20	4.61	16.0	3.03	26.5	10.79
# 45	5.50	3.80	9.2	1.74	28.5	5.82
# 60	7.50	2.71	4.5	1.12	20.9	2.18
# 80	7.20	1.65	2.7	0.74	7.7	0.84
# 120	5.60	0.83	2.6	0.38	2.9	0.33
# 170	3.60	0.31	1.7	0.14	1.2	0.12
# 230	2.10	0	1.0	0	0.7	0

sieve size	channel 7/4		channel 7/5		channel 7/6	
	weight retained (gm)	cumulative % finer	weight retained (gm)	cumulative % finer	weight retained (gm)	cumulative % finer
3.0 "	0	100	0	100	0	100
2.5 "	0	100	0	100	0	100
2.0 "	0	100	433.5	92.67	0	100
1 7/8 "	0	100	0	92.67	0	100
1 3/4 "	0	100	0	92.67	0	100
1.5 "	0	100	350.1	86.76	116.1	97.78
1.0 "	448.3	91.36	767.0	73.79	745.2	83.51
7/8 "	343.3	84.75	252.3	69.53	324.1	77.30
3/4 "	321.6	78.55	186.1	66.39	335.2	70.89
5/8 "	421.8	70.43	289.9	61.49	628.6	58.85
1/2 "	475.7	61.26	332.8	55.86	539.2	48.53
3/8 "	398.7	53.58	507.2	47.29	586.7	37.29
1/4 "	475.8	44.42	598.1	37.18	582.8	26.14
# 4	301.7	38.60	343.4	31.38	398.6	18.50
# 5	172.6	35.28	170.3	28.50	168.5	15.28
# 8	446.3	26.68	378.7	22.10	326.2	9.03
# 10	164.6	23.51	121.6	20.04	65.3	7.78
# 14	31.4	18.53	24.3	16.95	20.6	6.10
# 18	31.0	13.60	22.5	14.08	13.6	4.99
# 25	24.7	9.68	22.4	11.23	8.8	4.27
# 35	19.5	6.59	27.5	7.72	7.1	3.70
# 45	15.0	4.21	30.1	3.89	7.1	3.12
# 60	10.0	2.62	19.8	1.36	10.7	2.24
# 80	6.8	1.54	6.60	0.52	12.7	1.21
# 120	5.3	0.70	2.5	0.20	9.4	0.44
# 170	2.9	0.24	1.0	0.08	4.0	0.11
# 230	1.5	0	0.6	0	1.4	0